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Mobility Research for Future Vehicles

A Methodology to Create a Unified Trade-Off Environment for Advanced Aerospace Vehicle

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NIA Point of Contact (PoC):

Carole E. McPhillips
Deputy Contracts Manager
National Institute of Aerospace
100 Exploration Way
Hampton, VA 23666-6186
(757) 325-6762 (office)
(757) 325-6701 (fax)
carole.mcphillips@nianet.org

ASDL Technical PoC:

Dimitri Mavris
Boeing Prof. Advanced Systems Design
dimitri.mavris@aserospace.gatech.edu

Kyle Collins
Research Faculty
kyle.collins@asdl.gatech.edu



Aerospace Systems Design Laboratory
Guggenheim School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150
www.asdl.gatech.edu

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1 Introduction

The development and implementation of advanced aerospace vehicles is an endeavor that can potentially affect long term aviation operations and future system capabilities for several decades. Selecting the best vehicle configuration(s) requires a thorough understanding of the capabilities and life-cycle considerations required by the end user, the vehicle's full spectrum operations, as well as technologies impacting both operational needs and system performance. The fundamental goal of the proposed effort involves using the Aerospace Systems Design Laboratory (ASDL) established expertise in the fields of decision support and advanced vehicle modeling and simulation (M&S) to develop an innovative trade-off environment for advanced vehicle concepts exploration.

Over the span from October 2010 to September of 2016, a Capability Assessment and Trade-off Environment (CATE) with accompanying Excel tool was developed. The environment is powered by surrogate models created from the NASA Design and Analysis of Rotorcraft (NDARC) code. The surrogate models were created from data obtained through experiments performed in NDARC using candidate Joint Multi-Role Rotorcraft configurations (Single Main Rotor, Compound, and Tilt-rotor). The use of surrogates for distinct concept families provides a novel way of doing rapid trades to investigate how performance and vehicle unit cost vary across the different designs. To assess technology impacts on vehicle capabilities, CATE includes an Interactive Reconfigurable Matrix of Alternatives (IRMA) that allows for input and management of technologies. CATE uses Quality Function Deployment (QFD) style qualitative analysis for technologies that do not necessarily affect mission performance but do affect mission effectiveness. Users can assess technologies by manually selecting options using the IRMA or by using a genetic algorithm to perform a selection based on the user's objectives [1].

This fiscal year work aimed to extend the capabilities that currently exist in CATE. To increase the fidelity of the results in CATE, a comprehensive rotor performance analysis using RCAS (Rotor Comprehensive Analysis System) has been used to calibrate a new NDARC model that is then integrated directly into CATE. To increase the accuracy of the calibration, an optimization algorithm has been wrapped around Wayne Johnson's Rotor Performance Spreadsheet, varying the available NDARC variables to best match the calibration data. This process provides a quick and efficient way to calibrate CATE to new models, increasing the tools flexibility and accuracy.

To improve the capabilities of the IRMA in CATE, an extensive rotorcraft technology literature search was performed in order to capture new rotorcraft technologies. During the literature search, different technologies were identified, along with their impacts on the various components of the rotorcraft (i.e. physical/functional). These impacts were then modeled in the CATE environment through the use of tech factors on NDARC parameters. This work ultimately allows for new technologies to be rapidly assessed on a baseline architecture.

In order to extend the actual modeling capabilities, investigation on how OpenMDAO can be used to solve Multidisciplinary Design Analysis and Optimization (MDAO) problems was performed. The open source software was evaluated as a mean to interface with NDARC and perform calculations on the results.

The capabilities of CATE were demonstrated for an existing vehicle, the UH-60 Black Hawk. First, a new procedure to calibrate NDARC files was illustrated for the UH-60A and UH-60L. The power required, power available and component weights were calibrated with published data. Technologies were implemented on the vehicle model and the performance and sizing impacts were derived. Among them, the technologies used to perform the UH-60L to UH-60M upgraded were implemented and the characteristics of the derived UH-60M were analyzed.

The use of an integrated discrete event simulation model to estimate Reliability, Availability, Maintainability (RAM for rapid system trade-off analysis will be illustrated. The use of discrete event simulation tool is essential to this method as it enables designers to evaluate different concepts to achieve a desired Operational Availability (Ao) and affordability.

2 Report on Work Completed

2.1 Rotor Performance Spreadsheet Updates

This section describes the work done to integrate higher fidelity rotor analysis capability to CATE. Rotor Comprehensive Analysis System (RCAS) is used to perform this analysis and the results are presented in the following sub-sections.

2.1.1 Rotor Performance Analysis with RCAS

As the first attempt at the integration of higher fidelity analysis capabilities into the CATE, a comprehensive rotor performance analysis using RCAS has been performed and connected to CATE, as shown in Figure 1. The integration of RCAS into the CATE environment is carried out in three steps. First, a performance sweep of blade loading and advance ratio is run in RCAS to obtain the rotor induced and profile power required during flight. Next, an optimization technique is used to create an NDARC model by calibrating a set of NDARC variables to match the results from the RCAS models. This NDARC model is then used within the CATE spreadsheet to obtain higher fidelity performance results in a computationally efficient approach.

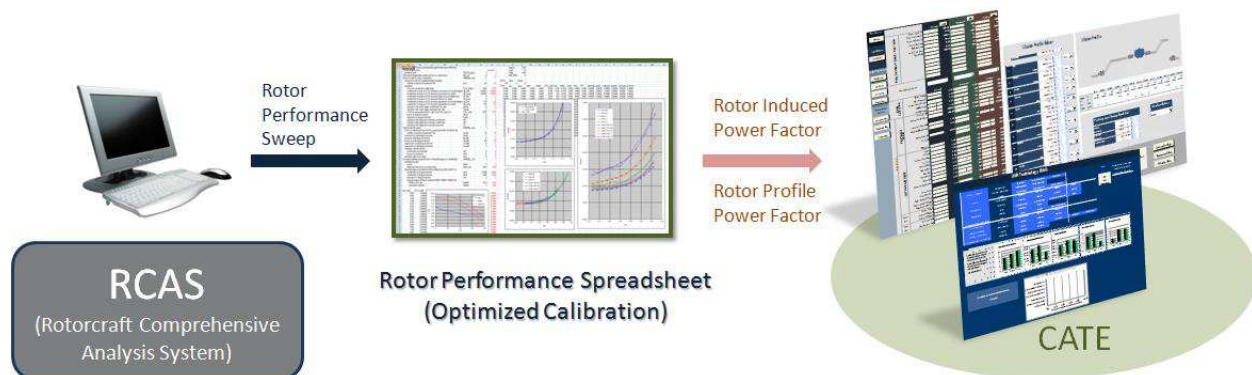


Figure 1 Integration Flow of the RCAS and the CATE

RCAS results were obtained for both hover and forward flight conditions using the standard UH-60A blade configuration with SC1095 and SC1094RB airfoils. The RCAS analysis option used in the study is a single blade analysis with dynamic inflow rotor model including dynamic stall and compressibility effects. The hover analyses was conducted at both sea level static, and 4,000ft 95F hot day conditions, while sweeping the blade loading between values of 0.07 ~ 0.17, which corresponded to a gross weight of 13,188 lbs to 32,018 lbs. Forward flight analyses was performed only at sea level static conditions, with the advance ratio being varied from 0.116 to 0.419, corresponding to flight speeds between 50 kts to 180 kts.

The RCAS rotor performance results were compared with the CAMRAD II results (which show good correlation with the UH-60 flight test data [2]) in Figure 2. The RCAS hover results match well with the CAMRAD II results for both sea level static and the 4,000ft 95F flight conditions in terms of total rotor power as well as the induced and profile component power values. The CAMRAD II results are included in the rotor spreadsheet provided with the NDARC package.

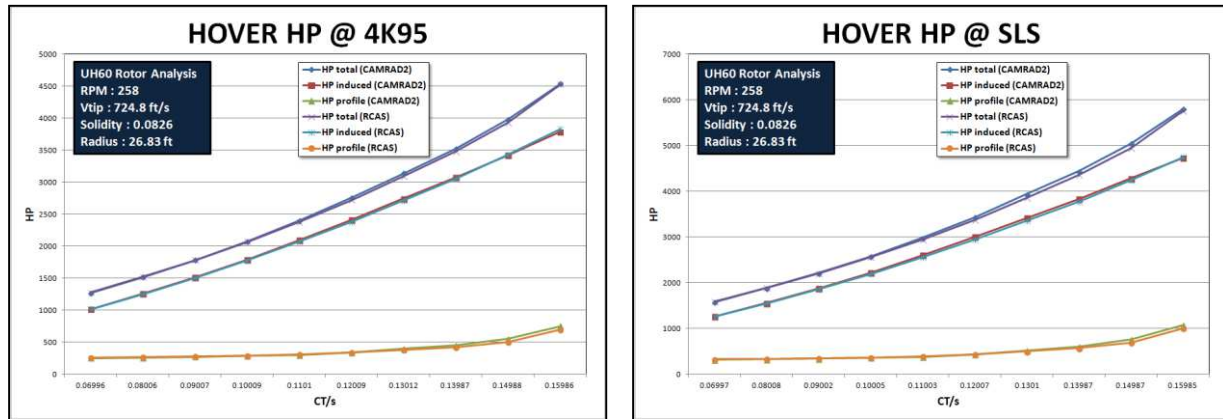


Figure 2 Rotor Hover Performance Comparison at SLS/4K95F (RCAS : CAMRAD II)

However, the forward flight results show discrepancies in induced and profile component power trends even though the total rotor power results are close to each other, as shown in Figure 3. This gap seems to result from the difference in the rotor inflow option between the free wake model in the CAMRAD II and the dynamic inflow model in RCAS, and requires a further investigation.

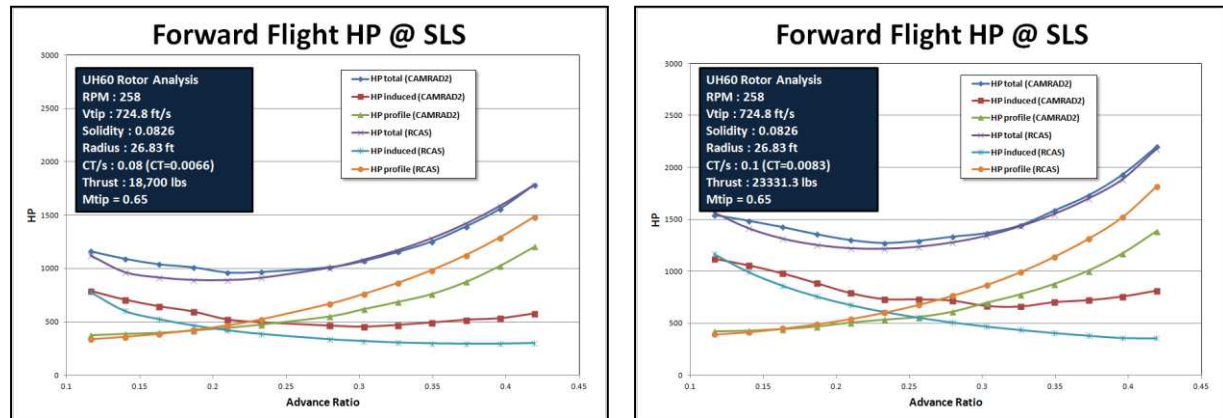


Figure 3 Rotor Forward Flight Performance Comparison at SLS (RCAS : CAMRAD II)

Due to these results, the rotor spreadsheet optimization task in this study has been performed with the RCAS hover results and the CAMRAD II forward flight results combined. The optimized calibration approach, which is explained in more detail in the following section, demonstrated the ability to quickly and accurately calibrate a NDARC model to match the higher fidelity RCAS/CAMRAD-II data. Using the calibrated NDARC model, the new sizing results showed less converged weight compared to the current calibrated model. The reason has been investigated and found to be due to less hover power predictions in the new model, which could explain the vertical climb rate difference in the calibration model. CATE and NDARC investigations using the optimized variables will be continued and reported on in more details in the next year study. A more accurate UH-60A calibration model is expected to be obtained through this further investigation.

2.1.2 Optimization of NDARC Rotor Spreadsheet Calibration

The purpose of the NDARC Spreadsheet is to calibrate a set of NDARC variables to match higher fidelity models from CAMRAD/RCAS for various flight conditions (considering both hover and forward flight). The calibration aims to minimize the overall error between the NDARC predictions and higher fidelity models at all of the specified flight conditions. Currently, the process requires the user to manually perform iterations by changing the NDARC design variables, one at a time, until they are satisfied that the NDARC model approximates the higher fidelity data accurately enough. This leads to ambiguity in the results, as there is currently no direct way to quantify the accuracy of the results; rather, users rely on visually matching five graphs to determine if the curve fits from NDARC are matching the calibration data. Additionally, this process relies heavily on the user having knowledge on what appropriate values are for each of the design variables, and it severely restricts the exploration of the design space (made up of the different combinations of NDARC variables), as the manual iteration will likely hone in on a single local minimum, rather than finding the best global solution to minimizing the error. Finally, the use of manual iteration to perform this task is incredibly inefficient, especially if the task is repeated many times for a different set of calibration data.

To address the issues stated above, the calibration of the NDARC variables was treated as a multi-objective optimization problem. Using the process described in Section 2.1.1.3, the accuracy of the calibration is measured using two values: the error in forward flight and hover conditions. Minimizing the errors in both forward flight and hover simultaneously presents conflicting design objectives; reducing the error in forward flight creates a greater error in hover, and vice versa. Thus, there is not one single calibration

setting that is better than all others. Rather, the solution to this problem is a set of non-dominated designs, having the property that the performance in one objective cannot be improved without worsening the performance of the other objective. This set of solutions to the optimization problem is referred to as the "Pareto Frontier", an example of which is provided in Figure 4. The selection of the "best design" is the one that represents the best compromise between forward flight and hover conditions based on some preference by the user, which requires a multi-objective decision making (MODM) technique. This is achieved through the use of the NSGA-II (Non-Dominated Sorting Genetic Algorithm II) optimization algorithm, as described in the following sections.

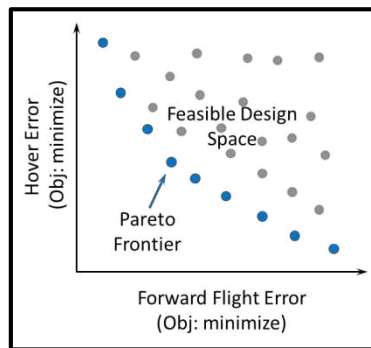


Figure 4 Pareto Frontier demonstrating the tradeoff in optimality between minimizing error in forward flight and hover

2.1.2.1 Optimization Overview

The use of optimization techniques to automate the calibration of the NDARC spreadsheet relies on two things: the set of NDARC design variables is fixed and known to the user, and the calibration data set is known and can be provided in some structured format. With this information, enough structure is provided to allow the entire process to be automated, requiring minimal user set up while providing fast, accurate results given that the information provided is appropriate. An overview of the new calibration process is provided in Figure 5, which requires four steps:

1. In the NDARC Calibration spreadsheet, select which NDARC variables are design variables for the optimization process versus constant parameters, and set the calibration data
2. Run the NSGA-II optimization algorithm
3. Load the Pareto Frontier of the calibration data set into the NDARC spreadsheet
4. Use a multi-objective decision making technique (TOPSIS) to select best compromise design based on the user preference of minimizing error in forward flight versus hover

It is likely that the user will have to iterate on this process by setting different bounds or values for the design variables, or even changing which variables will be optimized and which will be held constant. However, the process is designed such that these iterations can be done rapidly, requiring the user to simply set the new design variables and corresponding values, then click a button to run the optimization and load all of the results. The run time is expected to be on the order of 1-2 minutes, but may vary depending on the number of design variables selected.

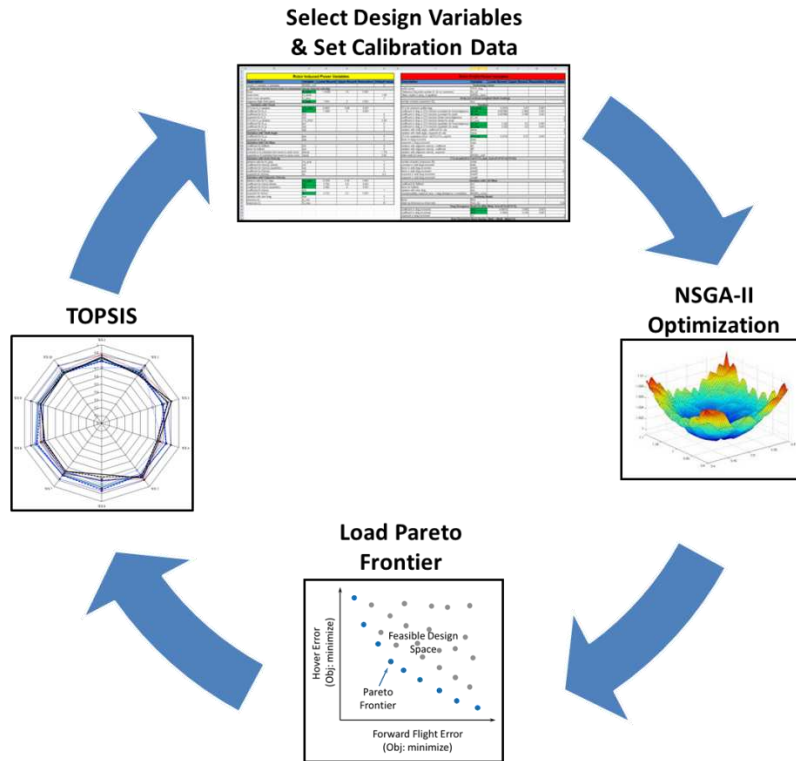


Figure 5 Automation of calibration process using optimization technique

2.1.2.2 Requirements to Run Optimization Process Properly

The calibration process is fully automated through the NDARC spreadsheet, requiring minimal effort for the user to set up the optimization problem. However, the implementation relies on a structured set of information in this spreadsheet that MUST be followed exactly. Additionally, the optimization process utilizes a Python code that has been compiled into an executable file, called “RunNDARC_Optimization.exe”. This executable, along with the required Python modules, must be located in a folder called “NDARC Optimization”. The “NDARC Optimization” folder must be in the same folder as the NDARC Spreadsheet in order for the automation process to work. An overview of each step in the calibration process is provided below.

2.1.2.3 Calculation of Calibration Accuracy

In the Rotor Performance Spreadsheet, the NDARC model is calibrated to match the five flight conditions listed below. The first three flight conditions are associated with forward flight, while the last two are associated with the hover flight conditions. To reduce the dimensionality of the Pareto Frontier of the design space, the errors associated with each of these five parameters were reduced to obtain a single error value for forward flight, and a single value for hover.

1. Calculate drag coefficient in forward flight at a fixed tip Mach number
2. Calculate the induced power coefficient (κ) in forward flight at a fixed tip Mach number
3. Calculate the drag coefficient in forward flight at a fixed blade loading (CT/s)
4. Calculate the drag coefficient in hover at a fixed tip Mach number
5. Calculate the induced power coefficient in hover at a fixed tip Mach number

To do this, for each of the five parameters the error is calculated as the sum of the squared relative error, where the value estimated from the curve fits is measured relative to the actual value provided by either the higher fidelity analysis tool (such as RCAS) or actual experimental data. This is shown below in Equation 1, where the errors are calculated for the drag coefficient and induced power coefficient in forward flight at a fixed tip Mach number (indicated by the “Mtip” subscript). This provides five error values, one for each of the parameters listed above.

$$(FF C_D Error)_{Mtip} = \sum_{i=1}^N \left(\frac{C_{d_{act}} - C_{d_{est}}}{C_{d_{act}}} \right)^2 \quad (FF \kappa Error)_{Mtip} = \sum_{i=1}^N \left(\frac{\kappa_{act} - \kappa_{est}}{\kappa_{act}} \right)^2$$

Equation 1

The final error for the forward flight and hover flight conditions is then calculated by taking the norm of the errors associated with each flight condition, as shown by Equation 2. This approach allows for the calibration of the NDARC models to be measured by two error values, rather than a five error values associated with each of the parameters being calculated by the Rotor Performance Spreadsheet. This simplifies the analysis for the user, and makes the Pareto Frontier easier to visualize.

$$FF Error = Norm[(FF C_D Error)_{Mtip}, (FF \kappa Error)_{Mtip}, (FF C_D Error)_{CT/s}]$$

$$Hover Error = Norm[Hover C_D Error, Hover \kappa Error]$$

Equation 2

2.1.2.4 NDARC Spreadsheet User Interfaces

Set Calibration Data

The calibration data is set separately on the "Calibration Data Sets" sheet of the NDARC Excel spreadsheet. Three sets of data are required for the calibration process, as shown by Figure 6, while the calibration variables are briefly described in Table 1. This data is specific to the curve fits developed in the NDARC spreadsheet, and is used to calibrate the NDARC variables to match the five flight conditions discussed in the previous section.

Forward Flight Calibration Data											
Cd and Kappa Calculations at fixed Mtip											
Case	mxz	CT/s	mxz	MAT	Actual Cd	Actual Kappa	mxz	CT/s	mxz	Actual Cd	Actual Kappa
1	0.1164	0.08003	0.0031	0.7249	0.00915	1.6695	0.008573202	1.208751032			
1	0.1395	0.08036	0.0348	0.74	0.00922	1.2597	0.008484978	1.261010102			
1	0.1928	0.08	0.007	0.7551	0.00919	1.3099	0.008823843	1.30551971			
1	0.186	0.08004	0.01	0.7701	0.00938	1.3779	0.009012788	1.36444885			
1	0.2091	0.08003	0.0133	0.7852	0.00969	1.3527	0.009240022	1.430847053			
1	0.2321	0.07995	0.0178	0.8002	0.00988	1.4311	0.00955802	1.69265525			
1	0.2777	0.07999	0.0261	0.8209	0.01048	1.6059	0.010572475	1.79575603			
1	0.3003	0.07993	0.0378	0.8447	0.01125	1.7029	0.011243073	1.779828079			
1	0.3225	0.08007	0.047	0.8593	0.0119	1.8927	0.01120214	1.88804358			
1	0.3445	0.08002	0.0573	0.8738	0.01255	1.997	0.01100453	2.005166993			
1	0.3659	0.07999	0.0697	0.8881	0.01372	2.3801	0.014270009	2.12902388			
1	0.3885	0.07999	0.0846	0.9021	0.01529	2.6588	0.01508113	2.370564895			
1	0.4044	0.08	0.1021	0.9157	0.01704	2.9807	0.01705068	2.581651938			
2	0.1164	0.10001	0.0022	0.7249	0.01035	1.0728	0.00939302	1.238803513			
2	0.1395	0.1	0.0036	0.74	0.01054	1.1629	0.009591602	1.280408832			
2	0.1928	0.09999	0.0053	0.7551	0.01029	1.2791	0.009891263	1.330462584			
2	0.186	0.09996	0.0077	0.7702	0.01049	1.3175	0.010071643	1.387175488			
2	0.2093	0.1	0.0102	0.7853	0.01086	1.3786	0.01034385	1.451171387			
2	0.2324	0.1	0.0138	0.8003	0.01113	1.3591	0.01070832	1.523026241			
2	0.2554	0.1	0.0182	0.8153	0.01116	1.485	0.01105687	1.602892888			
2	0.2784	0.10001	0.0238	0.8303	0.01165	1.6023	0.01175142	1.618192215			
2	0.3012	0.10001	0.0295	0.8452	0.01258	1.6025	0.012412781	1.78816834			
2	0.3239	0.09998	0.0384	0.86	0.01348	1.7123	0.012617342	1.89564687			
2	0.3463	0.1	0.0448	0.8747	0.01449	1.881	0.014878028	2.01091548			
2	0.3685	0.10001	0.0545	0.8893	0.01577	2.1317	0.015011843	2.134500251			
2	0.3904	0.1	0.0651	0.9038	0.01742	2.7056	0.016390152	2.281103333			
2	0.4118	0.09999	0.0775	0.9181	0.01953	2.8994	0.020558444	2.409564045			
2	0.4164	0.10008	0.08011	0.7249	0.01488	1.6699	0.013304283	1.264767895			
3	0.1391	0.11999	0.0025	0.74	0.01174	1.1704	0.01062037	1.07409725			
3	0.1929	0.11997	0.0038	0.7551	0.013	1.2481	0.014577803	1.355414484			
3	0.1882	0.12001	0.006	0.7702	0.01244	1.31	0.01543553	1.410488227			
3	0.2094	0.11999	0.0081	0.7853	0.01297	1.36	0.016701221	1.471671189			
3	0.2325	0.11998	0.0111	0.8004	0.01563	1.4819	0.016485852	1.649593759			
3	0.2557	0.11984	0.0138	0.8156	0.0161	1.4693	0.017462357	1.677517551			
3	0.2786	0.12004	0.0177	0.8306	0.01783	1.5588	0.01819291	1.90588910			
3	0.3018	0.12001	0.0227	0.8456	0.01985	1.7247	0.018311585	1.98959487			
3	0.3247	0.12013	0.028	0.8604	0.02243	1.9237	0.02154575	1.98971687			
3	0.3475	0.12	0.0348	0.8753	0.02405	2.0282	0.02320068	2.011976218			
3	0.3701	0.11999	0.0425	0.8901	0.02645	2.2558	0.025814629	2.132881142			
3	0.3925	0.12	0.0508	0.9048	0.0294	2.4485	0.029175274	2.261333365			
3	0.4147	0.11999	0.0606	0.9194	0.03345	2.7881	0.031997008	2.405477338			

Hover Calibration Data											
Hover Drag and Power Required											
Case	mxz	CT/s	mxz	MAT	Actual Cd	Actual Kappa	mxz	CT/s	mxz	Actual Cd	Actual Kappa
1	0	0.05997	0	0.6493	0.00819	1.085414445	0.008162	1.085			
1	0	0.08008	0	0.6493	0.00847	1.09154592	0.008455	1.085			
1	0	0.08002	0	0.6493	0.0088	1.099049515	0.008887	1.085			
1	0	0.10005	0	0.6493	0.0084	1.10919625	0.008487	1.085688			
1	0	0.11993	0	0.6493	0.0094	1.11944783	0.010195	1.103384			
1	0	0.12007	0	0.6493	0.01125	1.130735077	0.011989	1.118218			
1	0	0.13017	0	0.6493	0.0135	1.142835494	0.012688	1.120555			
1	0	0.13987	0	0.6493	0.0167	1.154804421	0.015688	1.153482			
1	0	0.14987	0	0.6493	0.0199	1.166817145	0.020735	1.166272			
1	0	0.15985	0	0.6493	0.0279	1.188705114	0.028264	1.182031			

Figure 6 Calibration data tables used to structure the information for the optimization code

Table 1 Description of variables required in the calibration data set

Variable	Description
mxz	Advance ratio along the x-axis
muz	Advance ratio along the z-axis
CT/s	Blade Loading (thrust coefficient / solidity)
MAT	Maximum Mach number at the advancing tip
Mtip	Blade tip Mach number
Actual Cd	Actual drag coefficient
Actual Kappa	Actual induced power coefficient

The optimization code is written to pull the data out of these specific tables. The tables can be of arbitrary length (the code will dynamically read the calibration tables until it has found the last row with data in it), but the column order MUST be followed exactly. Additionally, the first column of each table has a label for Case number. This is required in order to separate the data displayed on the graphs in the "TOPSIS"

sheet, so the user must take care to separate the data properly into different cases. For example, in the “Fixed Mtip” table, the case numbers differentiate between the data that pertain to different CT/s values.

The implementation of the calibration data set in this manner adds flexibility to the spreadsheet, as the user can now quickly change the calibration data set and run the optimization with very little effort. However, the code is limited to calibration data in this specific format. If for any reason the type of calibration data must be changed (e.g. no longer calculating values for drag, but some other parameter), both the NDARC spreadsheet and the optimization code will have to be altered to reflect this.

Setting Design Variables

The user interaction required to set up and run the optimization is contained within the “Optimization Set Up” sheet of the NDARC spreadsheet, which is labeled below in Figure 7. This interface provides the user with the ability to change which variables will be design variables (to be varied during the optimization) versus constant parameters, set the values of each variable, set a filename to save the optimization runs to, and a “Run Optimization” button that runs the entire optimization process based on the information in the current spreadsheet.

Figure 7 "Optimization Set Up" sheet of NDARC spreadsheet used to set up optimization problem

As noted in Figure 7, the current design variables being considered for the optimization problem have a green shaded background in the spreadsheet, while all constant parameters have white backgrounds. To change a variable between a design variable and a constant parameter, the user simply has to double click on the variable name itself, as clearly shown in Figure 8.

In addition, the values that the user must set for each variable are dependent on the type of variable. Constant parameters require only a default value to be set, which is simply the constant value they will be held at during the optimization process. For design variables, the NSGA-II algorithm requires that three values be provided: a lower bound, upper bound, and a resolution. These three values are required because the NSGA-II is a genetic algorithm, so all continuous variables must be discretized to some finite resolution, with each variable bounded on both sides. To make it clear to the user what values must be provided, only the necessary inputs for each variable are visible. This is clearly shown in Figure 7, where the design variables have values visible in the “Lower Bound”, “Upper Bound”, and “Resolution” columns, while the constant parameters only have values visible in the “Default Value” column.

Rotor Induced Power Variables						Rotor Profile Power Variables					
Description	Variable	Lower Bound	Upper Bound	Resolution	Default Value	Description	Variable	Lower Bound	Upper Bound	Resolution	Default Value
Model (1 constant, 2 standard)	MODEL_mf				2	Technology factor	TECH_drag				1
Induced velocity factors (ratio to momentum theory induced velocity)						profile power	Re_ref				0
hover	Ki_hover				1.12	Reference Reynolds number (0. for no correction)	MODEL_basic				2
axial climb	Ki_climb				1.125	Basic model (1 array, 2 equation)	Array (cd vs thrust-weighted blade loading)				24
axial cruise (propeller)	Ki_prop				2	Equation	ncd				
edgewise flight (helicopter)	Ki_edg				2	CTIs for minimum profile drag	CTIs_Dmin				0.07
Variation with Thrust						coefficient in drag vs CTIs function (constant for hover)	d0_hel				0.009
CTIs for Ki_h variation	CTIs_Hind				0.08	coefficient in drag vs CTIs function (constant for axial)	d0_prop				0
coefficient for Ki_h	h1				1	coefficient in drag vs CTIs function (linear hover/edgewise)	d1_hel				0
coefficient for Ki_h	h2				0	coefficient in drag vs CTIs function (linear for axial)	d1_prop				0
exponent for Ki_h	h2				2	coefficient in drag vs CTIs function (quadratic for hover/edgewise)	d2_hel				0.5
CTIs for Ki_p variation	CTIs_Pind				0.1	coefficient in drag vs CTIs function (quadratic for axial)	d2_prop				0.5
coefficient for Ki_p	p1				1.25	variation with shaft angle, coefficient for cdp	dprop				0
coefficient for Ki_p	p2				0	variation with shaft angle, exponent for cdp	xprop				2
exponent for Ki_p	p2				2	CTIs-CTIs_sep(X)	CTIs_sep				0.07
Variation with Shaft Angle						dsep	dsep				4
coefficient for Ki_p	hpa					xsep	xsep				3
exponent for Ki_p	xpa					d1	d1				0
Variation with Lift Offset						d2	d2				0
coefficient for f(offset)	ho1					xt	xt				2
factor for f(offset)	ho2					MODEL_stall					1
constant in Ki transition from hover to axial cruise	Mxail										
exponent in Ki transition from hover to axial cruise	Xaail										
Variation with Axial Velocity											
advance ratio for Ki_prop	mu_prop				1	number of points (maximum 20)	install				10
coefficient for Ki(mu) (linear)	ha1				0	constant in stall drag increment	fstall				4
coefficient for Ki(mu) (quadratic)	ha2				0	factor in stall drag increment	dstall1				4
coefficient for Ki(mu)	ha3				0	factor in stall drag increment	dstall2				80
exponent for Ki(mu)	xa				4.5	exponent in stall drag increment	xstall1				2
Variation with Edgewise Velocity						exponent in stall drag increment	xstall2				3
advance ratio for Ki_edg	mu_edg				0.35	Variation with Lift Offset					
coefficient for Ki(mu) (linear)	he1				0.8	coefficient for f(offset)	do1				0
coefficient for Ki(mu) (quadratic)	he2				0	factor for f(offset)	do2				8
coefficient for Ki(mu)	he3				1	variation with rotor drag	d3				0
exponent for Ki(mu)	xe				4.5	compressibility model (0 none, 1 drag divergence, 2 similarity)	MODEL_comp				1
variation with rotor drag	hea				0	Similarity Model					
minimum Ki	Ki_min				1.085	factor	fsim				0.09
maximum Ki	Ki_max				10	blade tip thickness-to-chord ratio	thick_sp				
						Drag Divergence Model (D=Mat.Mdd, Dcd=d1*D+d2*D.X)					
						coefficient in drag increment	dm1				0.056
						coefficient in drag increment	dm2				0.416
						exponent in drag increment	xm				3
						Drag Divergence Mach Number (Mdd = Mdd0 - Mddc1*c)					
						Mdd at zero lift	Mdd0				0.88
						derivative with lift	Mddc1				0.16

Figure 8 Demonstrating how to change variable type between design variable and constant parameter

A limitation of this process is that a value must be provided FOR EVERY column for the specified variable, as the optimization code is reading in these values and has no logic embedded within it to assign values to variables if they are missing from the spreadsheet table. That is, if a variable is a design variable, then the user must input a value for the “Upper Bound”, “Lower Bound”, and “Resolution”. The “Default Value” is hidden from the user for the design variables as it is not required for the optimization algorithm, but the current “Default Value” does not need to be deleted; it can be left as is. Likewise, for a constant parameter the “Default Value” column must be set, while the values for the “Upper Bound”, “Lower Bound”, and “Resolution” can be left as is, but will be hidden from the user. Because of this, checks have been built into the VBA script to ensure that the proper values have been assigned. Upon clicking the "Run Optimization" button, the VBA code will check all of the inputs, and provide alert messages if any input

values are missing. A few examples of this are shown below in Figure 9. The alerts will tell the user what variable to look at, what table the variable is in (either induced or profile power), and it will select the cell that needs to be changed.

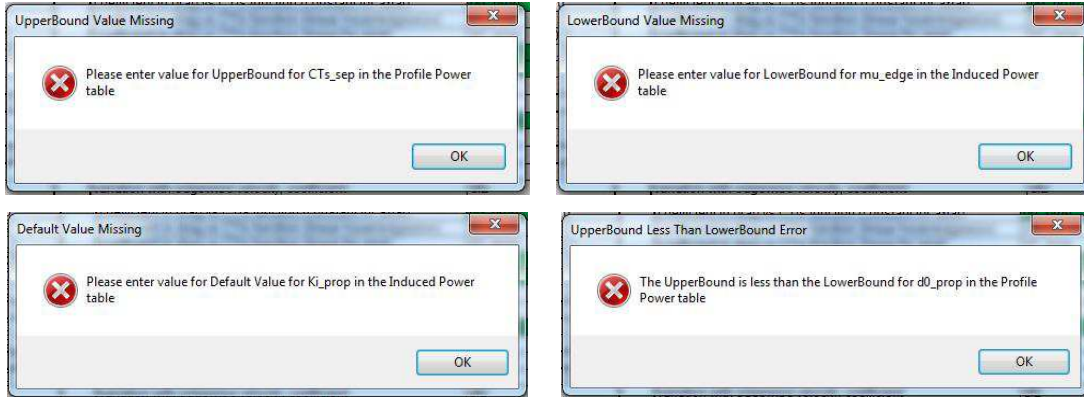


Figure 9 Possible error messages that occur when NDARC variables are not set correctly

2.1.2.5 Running NSGA-II Optimization

To determine the Pareto Frontier, the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) was implemented. The NSGA-II algorithm is a multi-objective evolutionary algorithm that optimizes a population of points to approximate the Pareto frontier of the design space. The result of the NSGA-II algorithm is thus an estimation of the Pareto Frontier of the design space, which then allows for the use of the multi-objective decision making technique to select the best compromise design. The NSGA-II algorithm is implemented externally to the NDARC spreadsheet in Python, which has been compiled into the “RunNDARC_Optimization.exe” executable. The executable file reads the NDARC spreadsheet to obtain the necessary information to perform the optimization. For more information on the NSGA-II algorithm, refer to the paper by Deb et.al [3].

2.1.2.6 Pareto Frontier of Calibration Data Set

Once the NSGA-II algorithm has determined the Pareto Frontier of the design space, the information must be loaded back into the NDARC spreadsheet so that it can be accessed to make an informed decision on the best set of NDARC variables. This is automatically done within the NDARC Spreadsheet, which loads the calculated errors and associated configuration settings into a table on a sheet labeled “Pareto Frontier Configurations”. Because there is no need for the user to interact with this sheet, and it in fact should not be changed by the user at all, this sheet should in general be hidden. For reference, a sample table is shown below in Figure 10.

Case	FF Error	Hover Error	Configuration Settings																		
			Kg_hover	KI_edge	CTs_Hind	ka1	ko2	Masial	mu_edge	ke1	ka2	Xc	CTs_Dmin	d0_hel	d0_prop	d2_hel	d2_prop	CTs_sep	dm1	dm2	M
1	0.098403727	0.006517255	1.088	1.649	0.088	1.312	8.194	1.12	0.274	0.538	0.164	3.597	0.053	0.008	0.008	0.671	0.598	0.095	0.009	0.604	0
2	0.072587033	0.01712874	1.04	1.645	0.106	1.439	8.194	1.12	0.274	0.538	0.164	3.597	0.053	0.008	0.008	0.671	0.598	0.095	0.009	0.601	0
3	0.072587033	0.01712874	1.04	1.645	0.106	1.439	8.194	1.12	0.274	0.538	0.164	3.597	0.053	0.008	0.008	0.671	0.598	0.095	0.009	0.601	0
4	0.073695965	0.015951299	1.054	1.645	0.109	1.312	8.198	1.12	0.274	0.538	0.164	3.597	0.053	0.008	0.008	0.671	0.598	0.095	0.009	0.602	0
5	0.071195365	0.014702948	1.054	1.645	0.109	1.439	8.198	1.12	0.274	0.538	0.164	3.597	0.053	0.008	0.008	0.671	0.598	0.095	0.009	0.602	0
6	0.091213925	0.006553566	1.073	1.645	0.088	1.439	8.198	1.12	0.274	0.538	0.164	3.597	0.053	0.008	0.008	0.671	0.598	0.095	0.009	0.604	0
7	0.07262344	0.01685731	1.041	1.645	0.106	1.439	8.194	1.12	0.274	0.538	0.164	3.597	0.053	0.008	0.008	0.671	0.598	0.095	0.009	0.599	0
8	0.075380172	0.011318852	1.057	1.645	0.102	1.439	8.198	1.12	0.274	0.538	0.164	3.597	0.053	0.008	0.008	0.671	0.598	0.095	0.009	0.6	0
9	0.093878511	0.006526577	1.088	1.649	0.085	1.439	8.198	1.12	0.274	0.538	0.164	3.597	0.053	0.008	0.008	0.671	0.598	0.095	0.009	0.602	0
10	0.076075462	0.010658882	1.07	1.645	0.109	1.439	8.198	1.12	0.274	0.538	0.164	3.597	0.053	0.008	0.008	0.671	0.598	0.095	0.009	0.601	0
11	0.097163771	0.006519995	1.086	1.649	0.088	1.439	8.198	1.12	0.274	0.538	0.164	3.597	0.053	0.008	0.008	0.671	0.598	0.095	0.009	0.602	0

Figure 10 Sample of the Pareto Frontier data on the "Pareto Frontier Configurations" sheet

2.1.2.7 Multi-Objective Decision Making Technique (TOPSIS)

The multi-objective decision making (MADM) technique implemented in the NDARC spreadsheet is the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). Details of TOPSIS can be found by a simple web search for "TOPSIS". Essentially, the TOPSIS technique requires that the user place weightings on the importance of the different requirements or design objectives, and then calculates the best (positive ideal) and worst (negative ideal) possible solution based on these weightings. The different designs are then ranked based on their distances from the positive and negative ideal solutions. TOPSIS simply provides a way to rank the designs on the Pareto Frontier to determine the best "compromise" design based on those weightings of the design objectives. It should be noted that this is purely a tool to aid the user in making a decision, and that other MADM techniques exist that will provide different results, which is purely due to difference in implementation.

TOPSIS is implemented on the NDARC spreadsheet in two separate sheets. The user interface is on the "TOPSIS" sheet, while all calculations required for the TOPSIS are all performed on a sheet called "TOPSIS Calculations". Like the "Pareto Frontier Configurations" sheet, the user should not change anything on the "TOPSIS Calculations" sheet, and for this reason the sheet is hidden from the user.

The user interface on the "TOPSIS" sheet is shown in Figure 11. The interface has two slider bars that allow the user to weight the importance of minimizing the error in the forward flight and hover conditions, respectively. The weightings are normalized such that they always sum to one; thus, an equal weighting implies that reducing the error in both flight conditions is of equal importance. The table shown displays the Top 10 ranked configurations or "Cases" from the current TOPSIS analysis, along with the magnitude of the calculated error and the NDARC design variables that each case represents. The "Case" number simply represents the case number assigned to each configuration in the table on the "Pareto Frontier Configurations" sheet. Any time that a slider bar is moved, the NDARC spreadsheet will automatically be updated to reflect the design that is ranked number 1. This is reflected in the graphs that represent the induced power and profile power plots.

If the user would like to see the results of a case that is not ranked 1, they can enter that case number in the “Case Number” box and click the "Update Configuration Case" button. This will load the specified case number into the NDARC spreadsheet, which again will be reflected by the induced power and profile power plots.

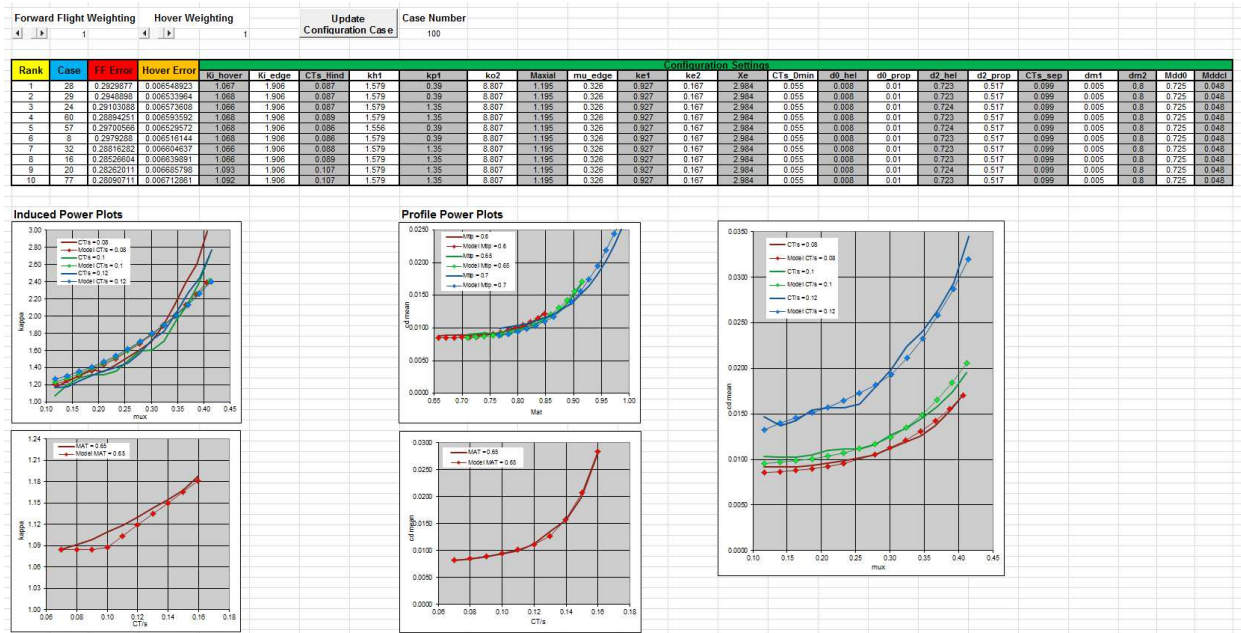


Figure 11 Sample TOPSIS user interface

2.2 Applicable Rotorcraft Technologies

2.2.1 Introduction to Technology Identification

In order to better capture technology impacts within the CATE environment, an extensive rotorcraft technology literature search was performed. The focus of this literature search was on single main rotors (i.e. UH-60). During the literature search, different technologies were identified, along with their impacts on the various components of the rotorcraft (i.e. physical/functional). This led to a rotorcraft technology taxonomy where the physical and functional decompositions of technologies were categorized. Finally, research was conducted to determine how to best represent these technologies effectively and efficiently within the CATE environment.

2.2.2 Process

This process, outlined in Figure 12 below, begins with a literature search to discover the emerging rotorcraft technologies. This literature search encompassed many reports and papers relating to rotorcraft technologies. The next step was to determine which areas of the rotorcraft system were affected by each technology, which was accomplished in two components as described below.

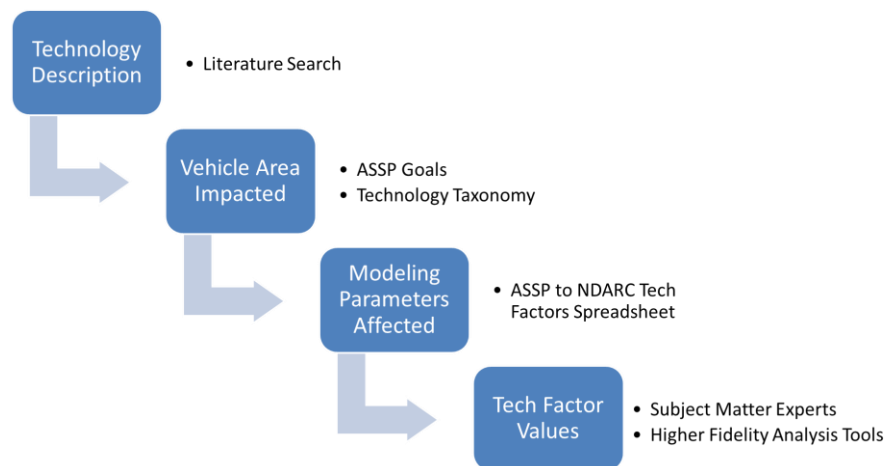


Figure 12 Technology Identification Process

The first component of the vehicle impact assessment step was to determine an overall breakdown of where each system of technologies is located on the vehicle, which resulted in the construction of a rotorcraft taxonomy. This taxonomy includes major rotorcraft systems such as: the rotor, engine, transmission, etc. These groups of systems were further broken down based on the function of the individual technologies. For example, rotor-related technologies were broken down into technologies related to active rotor systems, rotor planform alterations, and retreating stall delay. This grouped technology list, including system breakdowns, can be seen in the technology taxonomy in Figure 13.

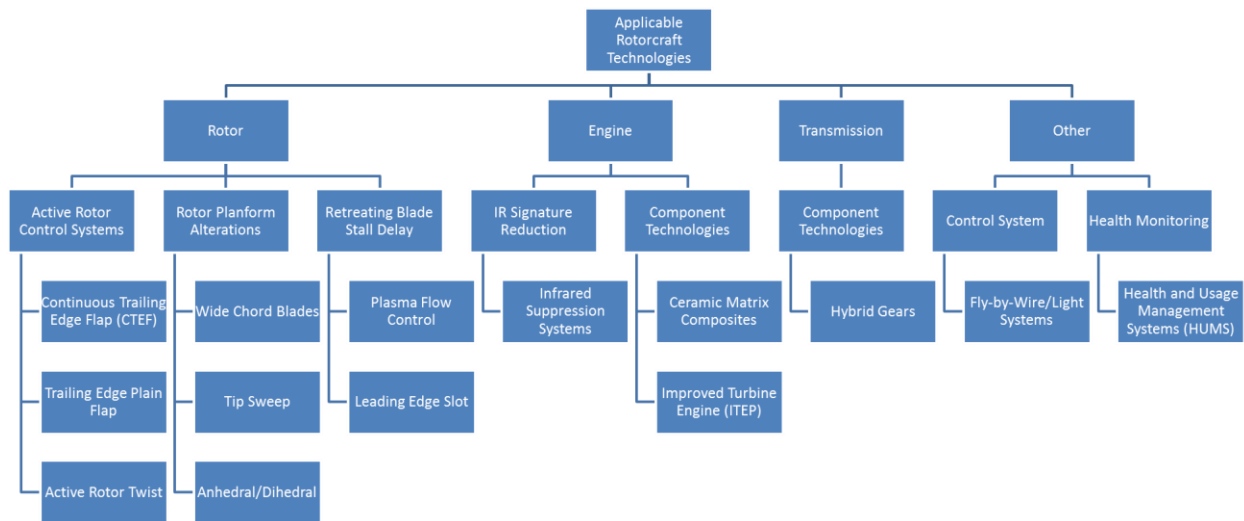


Figure 13 Identified Technology Taxonomy

The second component of this step was to break down specifically where each technology will impact the vehicle. Because this is a more complicated component, it was important to look into how the current rotorcraft world breaks down the rotorcraft from a technology point of view. This search resulted in the discovery of the Aviation Science & Technology Strategic Plan (ASSP). This plan includes future objectives for various rotorcraft systems and is broken down into various focus areas. The focus areas applicable to the technology research are shown in Figure 14. Each ASSP focus area is further broken down into more specific components, as shown in Figure 15.

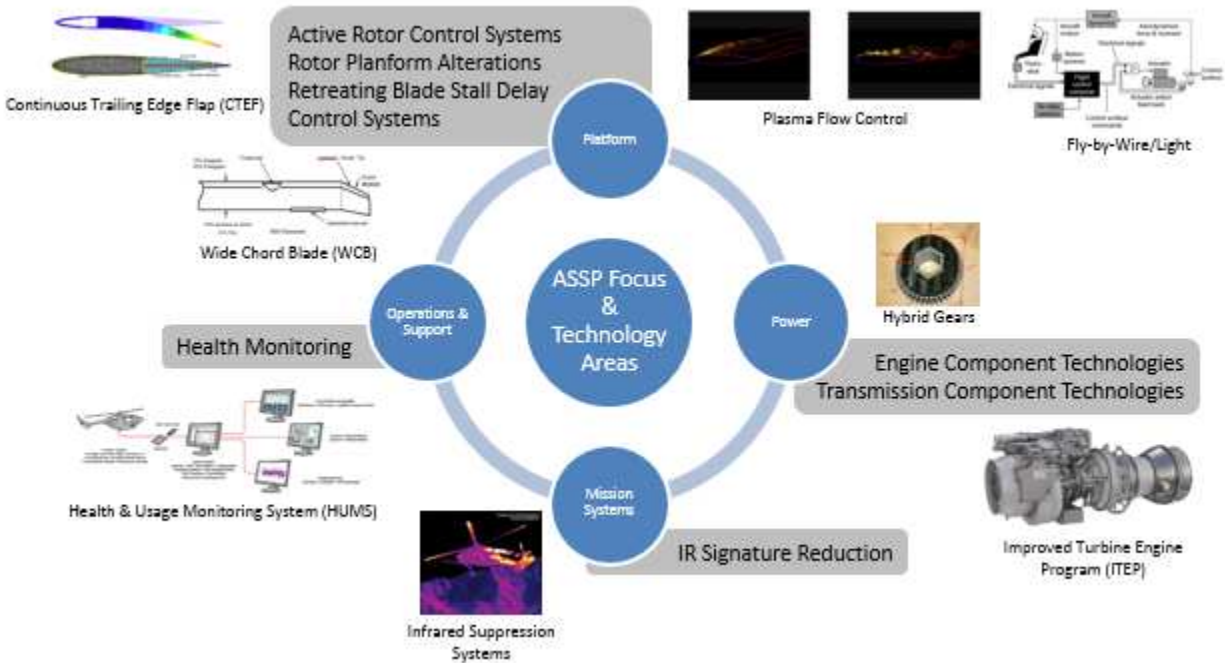


Figure 14 ASSP Focus & Technology Areas

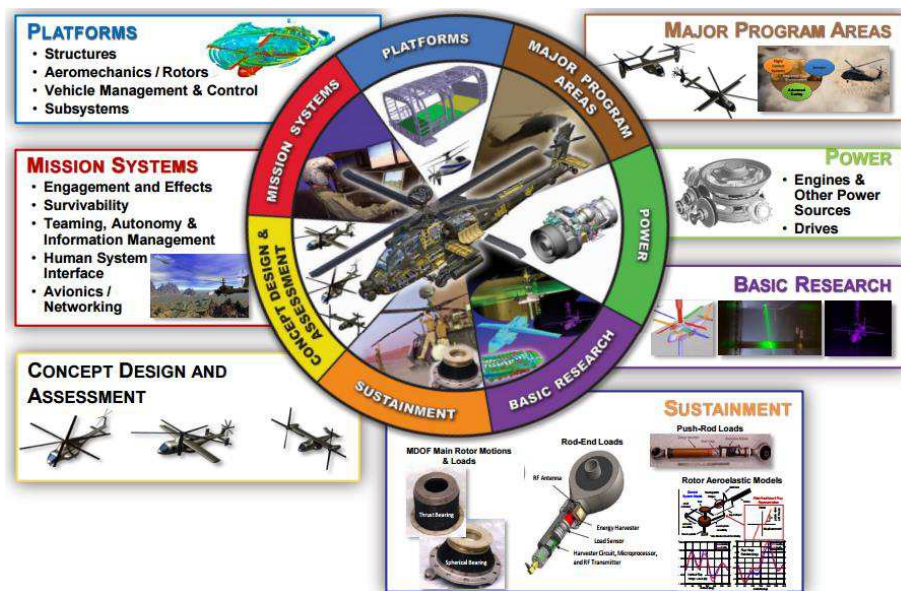


Figure 15 ASSP Focus Area Breakdown [4]

This focus area breakdown is then further broken down into specific technology objectives. This helped to determine what kind of impacts a given technology may have. For example, the Aeromechanics subgroup of the Platforms group is broken down as shown in Figure 16.

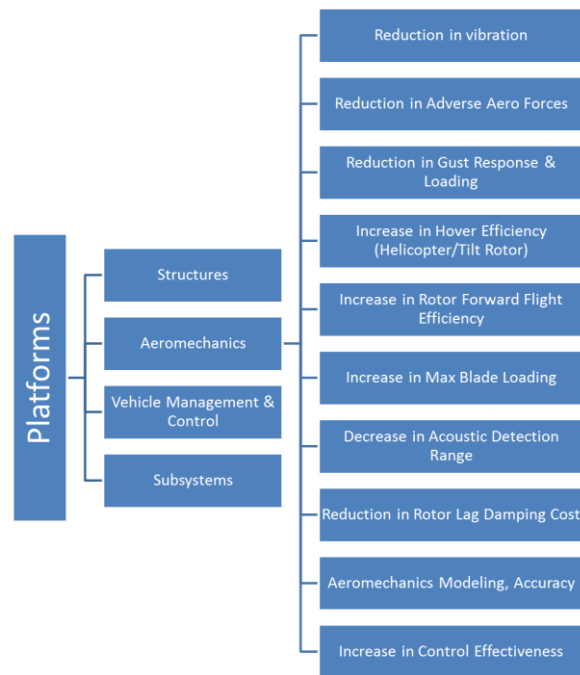


Figure 16 Aeromechanics Breakdown

Due to the fact that CATE uses surrogates powered by NDARC, each ASSP technology objective was then mapped to specific NDARC parameters. This helped to determine which NDARC parameters (or tech factors) were affected by each technology based on the technology’s expected impact. A snapshot of such mapping is found in Figure 17. The blue fill in Figure 17 indicates that the tech factor above related to the ASSP technology objective to the left.

ASSP Technology Objectives			NDARC Tech Factors														
System	Sub-System	Metrics (Technology Objectives)	TECH_1mg	Fix_1mg	Doc1	CD	MDrag	Doc1	Doc1_F4	CD_F4	CD_F4	Doc1_F4	CD_F4	Doc1_F4	CD_F4	Doc1_F4	CD_F4
Platform	Aeromechanics	Reduction in vibration															
		Reduction in Adverse Aero Forces															
		Reduction in Gust Response & Loading															
		Increase in Hover Efficiency (Helicopter/Tilt Rotor)															
		Increase in Rotor Forward Flight Efficiency															
		Increase in Max Blade Loading															
		Decrease in Acoustic Detection Range															
		Reduction in Rotor Lag Damping Cost															
		Aeromechanics Modeling, Accuracy															
		Increase in Control Effectiveness															

Figure 17 ASSP Technology Objective to NDARC Tech Factor Mapping

The final step in this process was to determine the specific NDARC parameter values associated with each technology. This process is different for each technology but has some inherent similarities. Using the

information found in the literature search it is possible to determine these parameters in a number of ways. The first is to use direct percentage decreases (or increases) to specific parameters found in the literature. For example, if an engine technology is expected to reduce SFC by 10%, the SFC NDARC parameter is multiplied by 0.90. Another possible method is to use expected performance improvements of a given technology and reverse engineer the associated tech factors. For example, if an engine is expected to have a given power available at various altitudes and velocities, these “sweeps” can be created in NDARC and various tech factors can be varied in order to match the power available within an acceptable error threshold. The final method is to use the knowledge of subject matter experts (SME’s). Their knowledge about where a technology is expected to be at in the future will help determine what modeling parameters need to be changed and by what amount.

For each technology listed in Figure 13, the associated technology objectives and resulting NDARC tech factors were identified. For some of the technologies, actual NDARC tech factor values were determined. The technologies are detailed in the following section.

2.2.3 Identified Technologies

The full list of applicable rotorcraft technologies identified is shown in Figure 13. As previously stated, it is important to note that this list is not all-inclusive. There are many more rotorcraft technologies being considered, but this method can be applied to more in the future and will allow researchers to determine where the technologies fit into the aforementioned taxonomy.

2.2.3.1 Rotor Technologies

Continuous Trailing Edge Flap (CTEF)

Unlike a conventional flap, the Continuous Trailing Edge Flap (CTEF), as the name implies, does not have a break in the trailing edge of the wing. Developed by the Army Research Lab (ARL), the CTEF utilizes an optimized biomorph designed with Macro-Fiber Composite (MFC) actuators to change the camber of the airfoil section in order to provide primary flight control for a rotorcraft (both collective and cyclical pitch controls) [5]. According to ARL in regards to the CTEF, “more efficient aerodynamic excitation combined with a simplified structural design will reduce vibration and permit in-flight blade tracking, thereby reducing maintenance costs for Army rotorcraft” [6]. A depiction of the CTEF can be seen in Figure 18 below.

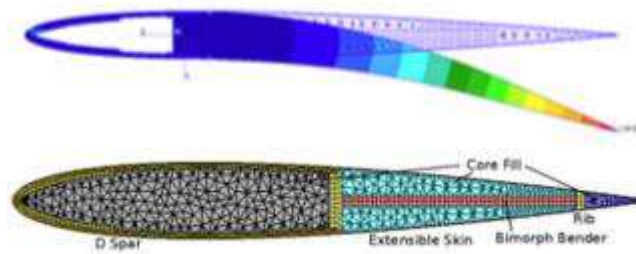


Figure 18 Cross-sectional View of the CTEF

Given the CTEF is a rotor-related technology, most of its impacts are within the Aeromechanics group of the ASSP goals. The following list includes the technology objectives that may be affected by including the CTEF on the vehicle:

- Reduction in Vibration
- Reduction in Adverse Aero Forces
- Increase in Hover Efficiency
- Decrease in Acoustic Detection Range

Due to the complexity of the CTEF, it is expected that there may be an increase in manufacturing cost, which is contrary to “Reduction in Manufacturing Cost” technology objective within the structure group. Using the ASSP Technology Objective to NDARC tech factor mapping spreadsheet, along with some good engineering judgment, the NDARC parameter set shown in Table 2 was selected to be used to model the CTEF within NDARC. Utilizing the results of a questionnaire given to a subject matter expert done in a previous year of the project, NDARC parameters were varied to match the expected SME projections. The NDARC parameters affected by the CTEF and their resulting percent changes are shown in Table 2. It is important to note that because the reduction in vibration cannot be directly modeled in NDARC, it is assumed that the reduction in vibration due to the CTEF can be related to a reduction in maintenance costs, as less rotor vibration would lead to less wear and tear on the rotors.

Table 2 CTEF NDARC Parameters

Baseline NDARC Factor	Percent Change from Baseline
Hover Induced Drag	-1%
Fuselage Body Weight	3.3%
Maintenance Cost	-24%

Wide Chord Blade

Another, more immediate, rotor technology is the Wide Chord Blade (WCB) (shown in Figure 19). The WCB offers increased lift due to a 16% wider chord blade compared to common rotors [7]. It is also constructed using advanced composites, rather than traditional rotor materials. Currently on the UH-60M rotor system, the WCB generates an additional 470 pounds of lift and its advanced design improves maneuverability and air speed [8]. Its all-composite spar also reduces maintenance man hours.

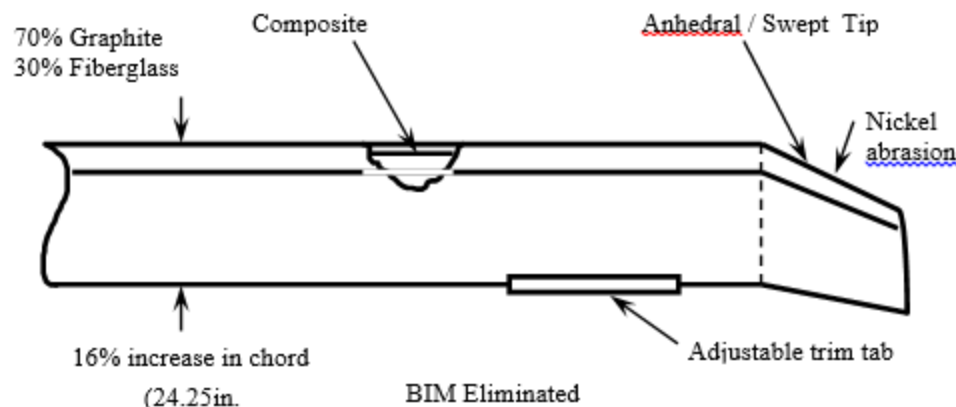


Figure 19 Wide Chord Blade

A literature search for the WCB system resulted in two useful sources of information for assessing the new rotor. Yeo et al. modeled the WCB system in a high fidelity code and found that the increase in solidity was the main performance driver because of de-loading the blades [9]. Thus it was assumed that the details of the aerodynamics would be captured by changing blade loading, which is a parameter on the TIM. It was found that the 10% increase in solidity reported for the WCB by Yeo et al results in a 9.1% decrease in blade loading [9].

Weight changes were based on results from Nixon's paper, which focused on modeling the structure of a composite rotor blade and using optimization to find minimum weight designs. His paper used the UH-60A as a validation case. Nixon's results for estimating blade weight changes due to composite designs were based on the aerodynamics of the UH-60A. Nixon concluded that a single-spar composite design would result in a 21.3% weight reduction and a multi-spar composite design, which would be inherently more ballistically tolerant, would result in a 12.1% weight reduction relative to the metallic design used for the UH-60A [10]. It is assumed that this weight reduction due to composite materials is applicable to the WCB because it uses an all composite blade.

Given the year of Nixon’s paper (1987), these weight estimates have a good deal of uncertainty. With the uncertainty in the weight reduction due to composite materials, the wide chord blade technology offers a good case for using distributions bounded by no weight change and a 21.3% weight decrease. However, for cases where distributions cannot be used, and because we do not know which structural design was used, the conservative prediction of 12.1% was selected. There was no specific information found on how the control weight would change, so no assumptions were made as to potential technology impacts for these. Finally, impacts for other technology factors, such as survivability or maintainability, were not researched given the performance focus of the use case. However, future work for demonstrating the maintenance discrete event simulator can use the WCB as an example technology.

From this literature search, it was determined that the following ASSP technology objectives were affected by the WCB system.

- Increase in Max Blade Loading
- Increase in Control Effectiveness
- Reduction in Structural Maintenance Labor
- Increase in Power to Weight

Utilizing the knowledge gained from the literature search, as well as the ASSP technology objectives under consideration, Table 3 summarizes the changes to baseline NDARC parameters for the WCB.

Table 3 Wide Chord Blade NDARC Parameters

Baseline NDARC Factor	Percent Change from Baseline
Blade Loading	-9.1%
Blade Weight	-12.1%

Plasma Flow Control

According to the Army Research Laboratory (ARL), “plasma based flow control is a potential active rotor technology that could lead to rotorcraft performance enhancement without increasing the rotor size.” This would lead to an increased payload capacity, higher achievable speeds, and increased range capabilities [11]. This could solve the dynamic stall problem that rotor blades can be prone to experiencing. Plasma based flow control delays the onset of flow separation (or stall). Figure 20 below illustrated flow visualizations for an uncontrolled airfoil vs. a plasma flow controlled airfoil.

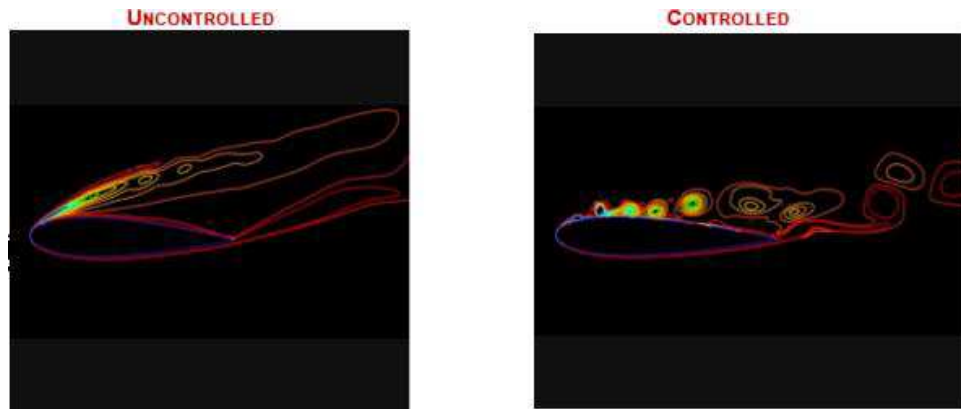


Figure 20 Uncontrolled vs. Controlled Plasma Flow Visualization

Most of the impacts of plasma flow control are in the Aeromechanics technology objective group. The following technology objectives have been identified to be potentially impacted by this technology:

- Increase in Rotor Forward Flight Efficiency
- Increase Max Blade Loading

These technology objective have all been identified because they will benefit from the reduced flow separation (i.e. stall) tendency that occurs at high forward flight velocities. Without aerodynamic losses due to stall, the rotor will have an increased forward flight efficiency and be able to sustain a higher loading. It also may provide the possibility for smaller rotor blades.

Given these technology objectives, the following NDARC parameters have been identified as possibly being impacted by the plasma flow control:

Table 4 NDARC Parameters Affect by Plasma Flow Control

NDARC Parameter	Description
Ki_prop	Axial Cruise Induced Velocity Factor
CWs	Blade Loading

2.2.3.2 Engine Technologies

Improved Turbine Engine Program (ITEP)

As the name implies, the Improved Turbine Engine Program is the US Army's initiative to develop a new turbine engine that weighs the same as the current UH-60L engine (the GE T700-GE-401C at 456 pounds) but produces 30% more shaft horsepower (increasing lift capacity by 27%), all while consuming 25% less fuel [12].

After conducting a literature search, the following ASSP technology objectives were identified that may be impacted by the ITEP engine.

- Lower SFC
- Increase in Power to Weight

The engine is also expected to have a higher unit cost which would increase engine procurement cost [12]. This is contrary to the “Reduction in Engine Procurement Costs” ASSP technology objective.

Utilizing the information obtained in the literature search, it was possible to determine certain NDARC parameters that needed to be changed. As mentioned above, the ITEP engine is expected to have a power rating of 3,000 hp IRP (30% more than the GE T700-GE-401C) and a weight of 456 pounds. The power improvement can be modeled directly in NDARC by increasing the Peng parameter to 3000. This automatically increases the engine weight when an NDARC sizing run is initiated. In order to counter this weight increase, the TECH_eng parameter was varied utilizing an optimization routine as a numerical solver to match the NDARC output engine weight to the expected 456 pounds. The results of this demonstration and the NDARC parameters that were changed are found in Table 2.

Table 5 ITEP Engine Demonstration

NDARC Input Parameter	Parameter Value
SLS Engine Power	3000
Engine Weight Parameter	1.773
NDARC Output Parameter	Parameter Result
Engine Weight	456.01

Ceramic Matrix Composite (CMC) Components

As improving engine efficiency has always been a goal within the aerospace community, ways to improve the turbine engine (used on rotorcraft systems) have been looked into. One such way is to utilize Ceramic Matrix Composites (CMC) for components within the turbine engine. These CMC components offer benefits of higher temperature capability and less cooling requirements. This leads to improved efficiency and reduced emissions [13]. Figure 21 illustrates a concept to utilize CMC's to develop turbine vanes.

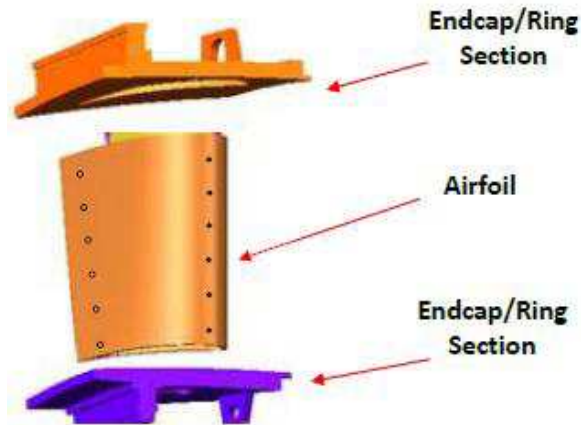


Figure 21 Ceramic matrix composite turbine vane concept

The following ASSP technology objective would be impacted by the use of Ceramic Matrix Composites within the turbine engine (all within the Engines group) [14]:

- Reduction in Engine Operating Cost
- Lower SFC
- Increase in Power-to-Weight

These would all have positive direction of improvement by the CMC components. The NDARC parameters that would potentially be impacted by the CMC components are listed in Table 6. In addition, utilizing a higher fidelity engine design/analysis tool (i.e. NPSS) would allow a technologist to obtain a more accurate representation of the CMC components' impact on the engine.

Table 6 NDARC Parameters Impacted by CMC Components

NDARC Parameter	Description
Tech_cost_maint	Maintenance Cost Technology Factor
sfcOC_tech	Specific Fuel Consumption at MCP Technology Factor
Tech_eng	Engine Weight Technology Factor

Hover Infrared Suppression System (HIRSS)

One of the most prominent sources of infrared detection on a rotorcraft is its hot engine exhaust gases, as can be seen in Figure 22. Reducing the infrared (IR) signature of rotorcraft, specifically those used in military applications, is highly desirable. Currently equipped on the UH-60M, the Hover Infrared Suppression System (HIRSS) provides shielding of hot engine exhaust gases in order to reduce the aircraft's infrared signature. This reduces the aircraft's susceptibility to be detected.

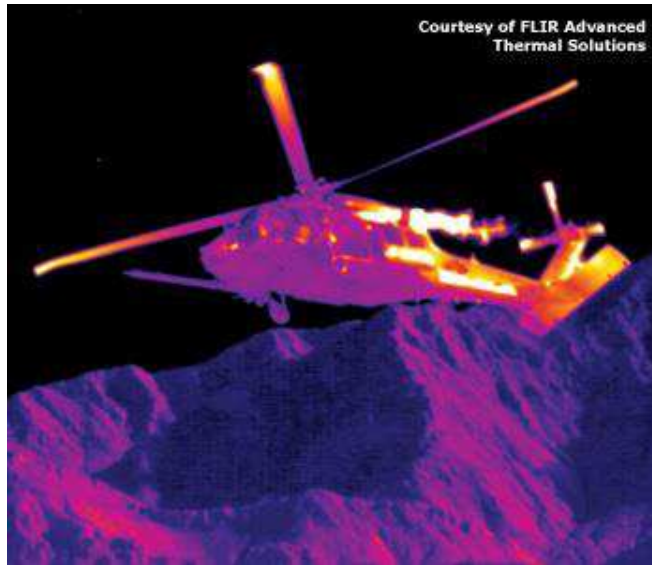


Figure 22 Rotorcraft infrared (IR) signature

The following is a list of the ASSP technology objectives that may be affected by the HIRSS. The list includes a combination of technology objectives from the Survivability, Aeromechanics, and Engines groups.

- Survivability
 - Reduced Visual/Infrared/Electro-Optical Signature
- Aeromechanics
 - Increase in Hover Efficiency
 - Increase in Rotor Forward Flight Efficiency
- Engines
 - Increase in Power-to-Weight

Of these technology objectives, only the one in the Survivability group is actually improved. The goal of the HIRSS is to reduce the infrared signature. The others actually see a degradation in performance. With the HIRSS turned on, the engine efficiency is decreased due to minimal power losses [15]. The engine weight may also increase due to the addition of such system, reducing the power-to-weight of the engine.

Utilizing the ASSP Technology Objective to NDARC Tech Factor mapping, the following NDARC parameters (Table 7) have been identified as potentially being impacted by the HIRSS. It is important to note that the Survivability aspects of the HIRSS cannot be modeled within NDARC as it is simply a rotorcraft design tool. Such parameters can be modeled in an Operations Model, such as the Discrete Event Simulator being developed as part of the overall CATE efforts.

Table 7 NDARC parameters impacted by HIRSS

NDARC Parameter	Description
TECH_drag	Profile Power Technology Factor
TECH_eng	Engine Weight Technology Factor

2.2.3.3 Transmission

Hybrid Gears

Though the use of composites in drive train systems is limited, hybrid gears are way to combine light-weight, high-strength composites with traditional metallic materials in order to provide a very high power to weight ratio [16]. A 20% decrease in weight as well as a reduction in noise and vibration can possibly be achieved [16]. A hybrid gear is illustrated in Figure 23 below.

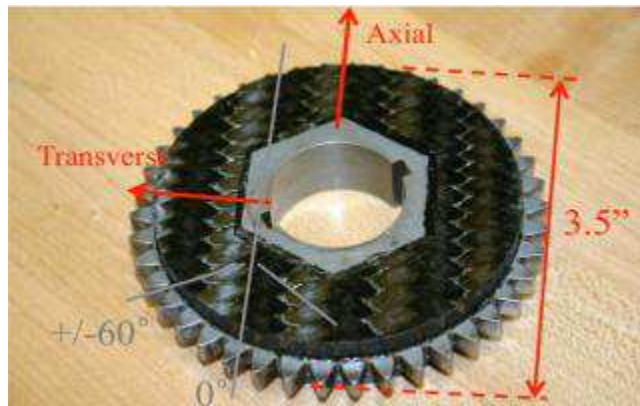


Figure 23 Hybrid Gear

Most of the impacts of the hybrid gears are located within the drive system of the rotorcraft. The following list includes the technology objectives that may be affected by including the CTEF on the vehicle.

- Lower SFC
- Increase in Power-to-Weight
- Reduction in Acquisition Cost
- Reduction in Drive System Generated Noise

Utilizing the SME questionnaire, the following NDARC parameters are affected with the associated percent change from baseline (Table 8).

Table 8 Hybrid Gears NDARC Parameters

Baseline NDARC Factor	Percent Change from Baseline
Gear Box Weight	-1.5%
Specific Fuel Consumption at MCP	-3%

2.2.3.4 Other Technologies

Health and Usage Management Systems (HUMS)

In an effort to reduce system failures on rotorcraft, systems are being developed to anticipate critical maintenance needs. One such system is the Health and Usage Management System (HUMS), which is described briefly in Figure 24.

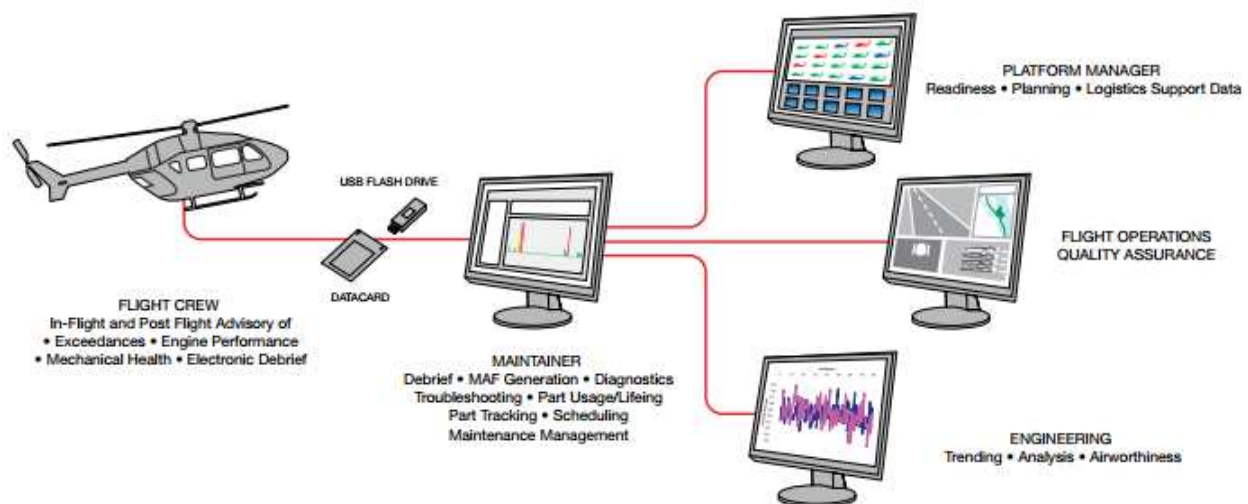


Figure 24 Health and Usage Management System Schematic

HUMS is a fleet-wide maintenance management system provides the following functions [17]:

- Engine Performance Assessment
- Rotor Track and Balance (RTB)
- Absorber Tuning
- Mechanical Diagnostics
- Exceedance Monitoring
- Usage Monitoring
- Ground Station Processing

With these functions, the goal of HUMS is to reduce fleet operating costs and improve performance by monitoring the usage and health of a vehicle [18]. The following ASSP technology objectives have been identified as potential areas of improvement with the addition of HUMS to the aircraft:

- Sustainment
 - Automatic Detection/Diagnostics of Critical Component Failures
 - Prognostics of Life/Maintenance Actions for Critical Components
- Subsystems
 - Decrease Maintenance Man-Hours

Given the nature of the HUMS technology, the only NDARC tech factor that is affected is TECH_cost_maint, which is the Maintenance Cost Technology Factor. The other factors can only be considered in an Operations Model, such as the Discrete Event Simulator being developed as part of the overall CATE efforts.

Fly-by-Wire/Fly-by-Light Systems

Fly-by-Wire (FBW) and Fly-by-Light (FBL) systems are currently used on many fixed wing aircraft, but due to the complexity of the control system, these types of systems are not yet common on rotorcraft systems. However, efforts are currently being made to incorporate these systems into rotorcraft. FBW systems utilize electrical signals to move actuators to deflect control surfaces or rotor blades, while FBL systems utilize a similar structure that uses fiber optics to transmit the control signals. A schematic of a Fly-by-Wire system compared to a traditional mechanical system is shown in Figure 25. These types of control systems are designed to improve system weight, handling qualities, system reliability, and maintenance time due to a reduction in moving parts that ultimately fail less frequently than conventional mechanical systems [19].

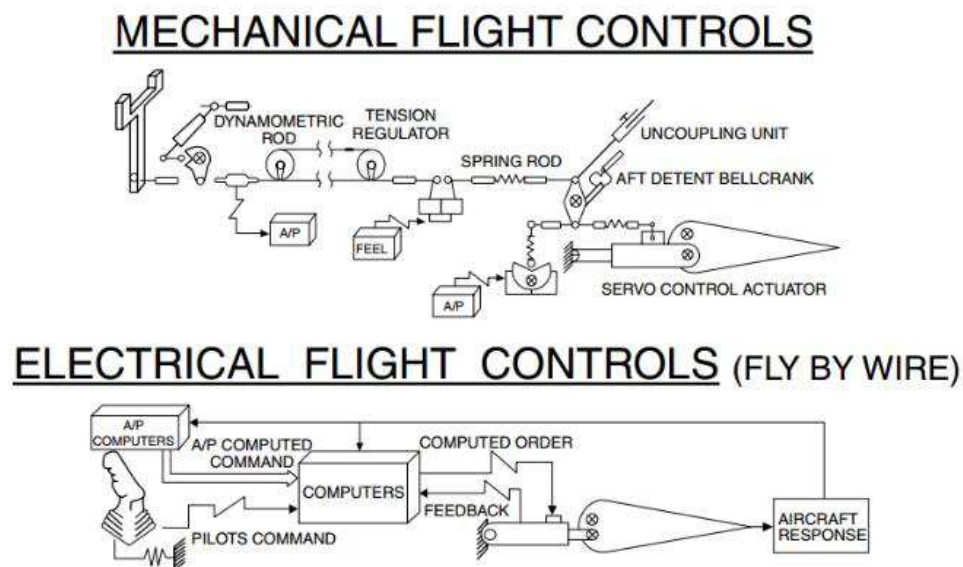


Figure 25 Fly-by-Wire vs. Mechanical Flight Controls

Utilizing the information found in the literature search of these systems, the following ASSP technology objectives have been identified as potentially impacted:

- Aeromechanics
 - Increase in Control Effectiveness

- Structures
 - Reduction in Structural Wt/DGW
- Subsystems
 - Decrease Maintenance Man-Hours

These systems would improve all of these objectives as aforementioned. The following NDARC parameters would be affected based on the ASSP technology objective to NDARC tech factor mapping described earlier:

Table 9 NDARC Parameters Impacted by FBW/FBL Systems

NDARC Parameter	Description
Tech_RWfc_b	Boosted Rotary Wing Flight Control Weight Technology Factor
Tech_RWfc_mb	Control Boost Mechanisms Rotary Wing Flight Control Weight Technology Factor
Tech_RWfc_nb	Non-boosted Rotary Wing Flight Control Weight
TECH_RWhyd	Rotary Wing Flight Control Hydraulics Technology Factor

2.3 Assist ARL in Integrating Tools into OpenMDAO

In an effort to support ARL in the integration of physics-based models, OpenMDAO was investigated as a possible solution to solve Multidisciplinary Design Analysis and Optimization (MDAO) problems. The work was based on previous analyses made by ARL.

OpenMDAO is a Python-based open source software that aims to integrate multiple disciplines analysis together and find optimal solution to multi-disciplinary problems. It is developed by developed at NASA Glenn Research Center which provides some support online[20]. The most recent distributions and archives of previous versions along with documentation are available online [21]. The team used OpenMDAO v0.13 on a Windows personal machine. It was noted that the installation requires the following software: Python, NumPy and SciPy [22].

Previous ARL work [23] [24] includes the use of OpenMDAO to generate NDARC rotor performance maps from published data and to integrate RCAS, a comprehensive rotor analysis code with NDARC. The NDARC wrapper for the case described in the papers was provided to the team by ARL. Even though OpenMDAO showed promise, it was found that the integration of the codes of different tools (such as MATLAB and importing text files) was not straightforward when compared to similar programs designed to perform the same task, such as Model Center and ISIGHT.

The work focused on the integration of the UH-60 NDARC files in OpenMDAO. Running the UH-60 NDARC task include opening the description files, modifying them with given sizing parameters, running the sizing task and parsing the output. The description files include the mission description, engine file and aircraft description. Unfortunately, the engine description files could not be parsed and read by OpenMDAO due to numbering convention in the file. The problem was identified, but the efforts to solve it were put on hold while the other tasks of the current report were being performed.

2.4 Operation and Maintenance Model

The primary focus of the FY16 work was to refine the model and present it at the American Helicopter Society (AHS) annual forum. Model refinement was focused on improving the robustness of the model and preparing it for integration with CATE. While working through the model some critical questions arose with regard to the operations portion of the model. Due to the time limitation with the AHS paper being presented, focus was placed on model verification with the questions to be addressed after. Following the presentation at the forum, discussions with the Integrated Product Lifecycle Engineering Laboratory (IPLE) on campus revealed an interesting opportunity to improve the model. The following sub-sections describe the overall goal of the operations model, the Discrete Event Simulation (DES) model as presented at the AHS forum, its limitations, the work done in collaboration with IPLE to improve the model, and future work for FY17. Furthermore, research into the addition of a combat phase to the operations model is being researched and initial findings are presented here.

2.4.1 Introduction

There is a big push in the vertical lift community to develop systems that are reliable and maintainable, for Department of Defense (DoD) acquisition. The DoD Reliability, Availability, Maintainability (RAM), Cost Rationale Report Manual (Ref. 25) describes ‘sustainment’ as a key component of performance and claims including sustainment planning upfront enables the acquisition and requirements communities to provide a weapon system with optimal availability and reliability to the warfighter at value. ‘Sustainment’ is made up of Availability (Materiel and Operational), Reliability, and Operations and Support (O&S) Cost. This paper will discuss the use of an integrated discrete event simulation model to estimate RAM for rapid system trade-off analysis. The use of discrete event simulation tool is essential to this method as it enables designers to evaluate different concepts to achieve a desired Operational Availability (Ao) and affordability.

2.4.2 Model as Presented at AHS Forum 72

The model presented at the 72nd American Helicopter Society annual forum was targeted at assessing technology impacts on the reliability, availability, and maintainability of a fleet of rotorcraft through discrete event simulation of the maintenance and operational lifecycles of the fleet. Vehicles were modeled as a container of parts, each of which accrued damage through normal fatigue during flight. Incorporation of technology factors allowed exploration of technology effects on operational availability, vehicle loss rate, operations and support costs, and maintenance metrics. Initial model

verification on a UH-60M baseline demonstrated expected trends in availability as well as the ability to model technologies which impact O&S costs, such as HUMS.

2.4.2.1 Modeling criteria selection

Affordability, availability, and maintainability were selected as the metrics to be calculated with the initial modeling capability described below. These objectives share a common thread of operations and support activities, such as maintenance. The maintenance of a vehicle can be expressed in terms of the metrics listed in Table 10.

Table 10 Maintenance Metrics

Metric	Units	Description
Mean Time Between Maintenance Actions (MTBMA)	hours	The fleet-wide average length of time between successive maintenance actions, which informs the length of missions and deployments (Ref. 26).
Mean Time to Repair (MTTR)	hours	The fleet-wide average length of time required to perform a maintenance action (Ref. 26).
Maintenance Man-Hours per Flight Hour (MMH/FH)	hours/hour	The fleet-wide average number of hours spent on maintenance actions and inspections required for each flight hour flown in the current environment (Ref. 27).
Cost Flight Hour (cost/FH)	\$/hour	The average recurring cost for each flight hour. This figure can be broken down into consumables, material, labor, and facilities (Ref. 28).
Excess Availability	%	The proportion of time that the vehicle is fully operational but not in use (Ref. 28).

The objectives for any technology are to maximize MTBMA, while minimizing MTTR, MMH/FH, and cost/FH. Excess availability should meet some desired threshold; as additional capability does not add value to the system.

Contemporary, top-down assessment of these attributes rely on close interactions with technologists and subject matter experts, and are usually expressed in a qualitative format. A more suitable approach is to create a bottom-up model for vehicle estimates based on low-level technology effects that can be determined from prototyping or literature review.

2.4.2.2 Conceptual Model

The model represents a fleet of rotorcraft staging from a forward operating base. Vehicles are passed through an operational cycle, flying missions and undergoing inspection and maintenance. The conceptual flowchart is shown in Figure 26.

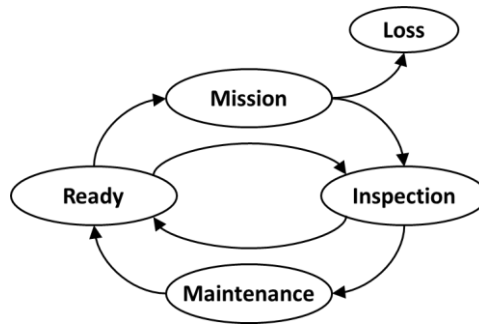


Figure 26 Conceptual Model Flowchart

Vehicle operations and support activities occur through discrete maintenance, inspection, and replacement actions that are either time-based (i.e. the replacement of a life-limited part or scheduled routine inspection), or trigger-based (i.e. post-flight inspection or the repair of a part damaged on mission) (Ref. 29). Therefore, a dynamic, discrete modeling methodology is required. Trigger-based actions also introduce stochastic effects on inspection and maintenance, which must be reproduced in the model.

2.4.2.3 Literature Review

A survey of dynamic, discrete modeling methods yielded three alternatives: Markov chains, Petri nets, and Discrete Event Simulation (DES). Discrete Event Simulation (DES) was ultimately chosen as it condenses the simulation time by only performing calculations when a time-based or event-based trigger is met, as opposed to a continuous system which must calculate every time step. Events are added to a list, which is stepped through chronologically in order to activate the relevant portions of the model. The tools examined for DES construction allowed the modeling of multiple types of tokens moving through the model, such as resources and personnel. Thus, Discrete Event Simulation was found to satisfy the modeling requirements identified within the conceptual model.

Discrete Event Simulation is a well-known simulation tool that has long been used for military systems (Ref. 30). Prior work utilizing DES for vehicle operations have focused on evaluating or optimizing operational methodologies, such as logistics (Ref. 31) or maintenance schedules (Ref. 32), while treating the vehicle as the fundamental object within the simulation. This level of

simulation still lacks the ability to model part-level technology effects, because these models work on failure and repair rates that are abstracted to the vehicle-level.

As part of their modeling and simulation effort, Arruda et. al. created a DES to model the full-spectrum operations of a rotorcraft fleet (Ref. 33). The model was developed in SimPy, an open-source module for Python. Arruda et. al. primarily used the DES to evaluate the effects of active rotor technologies on fleet availability and maintenance. Technology factors for vibration and noise were varied on a baseline vehicle to represent these effects. Operational metrics were found by simulating the damage and repair of individual vehicle components. The work reported in this paper re-uses this basic DES environment and builds upon it. This work retains the ability to model technology impacts on a fleet of vehicles, while expanding the scope of the simulation from a single configuration with fixed vehicle components in order to enable freeform vehicle configuration.

2.4.2.4 Technical Approach

The simulation is designed for a deployment of a rotorcraft at a forward operating base. The vehicle is passed through an operational cycle, flying missions and undergoing inspection and maintenance. This model is shown in Figure 27.

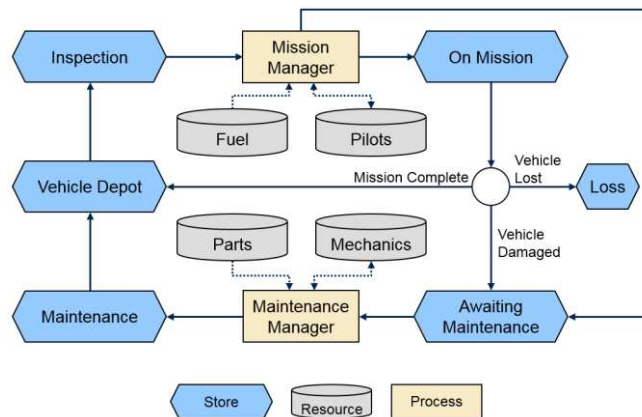


Figure 27. Discrete event simulation model flowchart showing stores, resources, and processes

The vehicles pass between stores, represented as hexagons in Figure 4, as directed by the processes, represented as rectangles. The Mission Manager manages transitions out of the Vehicle Depot, Inspection, and On Mission stores. The Maintenance Manager manages transitions out of the Awaiting Maintenance and Maintenance stores. At the start of the simulation, input variables are instantiated for the base, as listed in Table 11. The simulation is executed for a set amount of time, and runs until that time has expired or no new events are created.

Table 11. Base Input Variables

Input	Units	Description
Number of Pilots		The number of pilots available for a mission
Pilot Burden/FH	\$/hours	The direct cost of supporting a pilot for one flight hour
Fuel Cost	\$/gallon	The cost of aviation fuel
Number of maintenance personnel		The number of maintenance personnel available
Maintenance Start	Time of day	Time when the maintenance shop opens each day and becomes available for activities
Maintenance End	Time of day	Time when the maintenance shop closes each day and can no longer perform activities.
Number of parts		The quantity of each type of part stored at the base

2.4.2.5 Vehicles & Parts

Each vehicle is constructed as a container that is filled with parts. Parts can be created for any system on the vehicle, such as an engine, a rotor blade, or landing gear. At the start of the simulation, part objects are created and populated with values drawn from the input files. The part objects are then allocated to vehicle objects. All parts reside on the same level of hierarchy within the system.

Many different configurations can be modeled by adding the relevant parts because the vehicle is built from the component-level. A single main rotor can be modeled by including one main rotor part, or a tilt-rotor can be modeled by adding two props and the associated tilt mechanisms.

The use of parts can also allow different levels of simulation, depending on the detail of the parts. At the highest levels, parts can act as entities like ‘airframe,’ ‘rotor,’ and ‘engine,’ but these can be decomposed into parts such as individual rotor blades, structural linkages, and shafts, to suit the model requirements. Given the availability of data, the modeler can choose to create components at any desired level of detail.

Each part tracks the flight hours, damage, and total cost incurred throughout its lifetime. These metrics are calculated and updated according to the part’s input value types, listed in Table 12.

Table 12. Part Input Variables

Input	Units	Description
MTTR	hours	The mean time to repair the part, including uninstallation from the vehicle, repair to the component or replacement, and reinstallation.
Inspection Time	hours	The time required to perform a routine inspection on the component without removal.
Inspection Threshold	%	The cumulative damage threshold that will trigger component repair or replacement.
Lifespan	hours	The flight hours allowed for a life-limited component.
Unit Cost	k\$	The purchase cost for a new component.
Repair Cost	k\$	The mean cost in material to repair the component, excluding unit cost and labor.
Failure Mode	'flight' or 'fatigue'	Enumeration to determine how the model will track part usage and trigger maintenance.
Failure Effect	'abort' 'loss' or 'continue'	Enumeration that determines the effect of a part failure during flight.
Fatigue Properties		Stress as a function of cumulative number of cycles, based on an aggregate of the part, or based on a limiting material.

The simulation also tracks the number of times maintenance is performed on each part type. At the system level, the simulation tracks each vehicle's flight hours and time since previous maintenance activity.

2.4.2.6 Mission Manager

The Mission Manager determines when missions are generated, and randomly draws the mission from a weighted list of mission types created by the user. Each mission is created as a set of phases; an example is shown in Table 13.

Table 13. Phase Definition for a Combat Mission

Phase	Duration	Altitude	Temp	Payload
Hover	2.5 min	2500 ft	59 °F	1000 lb
Cruise	100 min	3000 ft	59 °F	1000 lb
Loiter	15 min	3000 ft	59 °F	1000 lb
Cruise	100 min	3000 ft	59 °F	1000 lb
Hover	2.5 min	2500 ft	59 °F	1000 lb

Phases can be arranged to represent different types of missions, such as attack, transport, scouting, or medevac. The mission is then assigned to an available vehicle in the Vehicle Depot at which time the vehicle undergoes preflight inspection and is allocated pilots and fuel.

The Mission Manager may also trigger any outstanding maintenance items the vehicle has accumulated. For instance, if the vehicle is inspected before the mission, and a part is found to be damaged or have exceeded its lifespan, the vehicle will be moved to maintenance, and another vehicle substituted on the mission.

The mission includes performance calculation and part damage calculation. Equations from Leishman (Ref. 34) are used to calculate fuel burn and vehicle g-loading for the selected mission. The vehicle speed is then used as the input to a vibration map in order to generate the vibration amplitude for use in part damage calculations. The vibration map was created as a regression on historical UH-60 information (Ref. 35). If a part's fatigue characteristics are supplied, part damage can be calculated via Miner's rule for cumulative damage (Ref. 36):

$$D = \frac{\sum_{i=1}^k n_i S_i}{NS} \quad (1)$$

Vibration and loading are calculated for each mission phase flown, and the results are used to increase the part's damage. Otherwise, the part lifespan is calculated directly from the input value for lifespan.

If a part exceeds its damage threshold, the part ends the mission according to its failure effect. Missions can be successfully completed with or without damage, aborted with damage, or the vehicle can be lost. If the mission is successfully completed or aborted, the Pilots are returned to the resource store. Consumables such as fuel and parts are not recycled.

2.4.2.7 Maintenance Manager

The Maintenance Manager determines whether the vehicle requires maintenance. If so, the vehicle is queued for the relevant maintenance actions, and is assigned parts and mechanics as they become available. Once the action is complete, the vehicle returns to the Vehicle Depot.

Vehicle-level maintenance actions are categorized into two groups: scheduled and unscheduled maintenance. Scheduled maintenance is triggered after a number of flight hours, or in set time intervals. Unscheduled maintenance involves repair or replacement of a part due to damage sustained during a mission. Maintenance actions for each part can currently be triggered in one of two ways: damage, or exceeding lifespan. Replacement or repair can be triggered simply by the part's total flight hours exceeding its lifespan. Alternatively, given information about the part's fatigue characteristics, replacement can be triggered by damage. This method assumes that the damage will be revealed by an inspection when the inspection threshold has been reached, and the part will fail once the damage reaches 1.0. The replacement by damage is designed to allow evaluation of active health monitoring (AHM) technologies, such as HUMS. This approach is best suited to parts that have a characteristic material that is most susceptible to fatigue, such as a driveshaft or rotor blade linkage, rather than complex components such as avionics.

2.4.2.8 Cost Modeling

Direct operating costs for each mission are calculated using labor burden for pilots and the cost of consumables, as shown in Equation 2:

$$C_{miss} = FH * B_p + C_{cons} \quad (2)$$

At the completion of the simulation, each mission cost is summed and the average cost per flight hour found. Maintenance costs for each activity are calculated by Equation 3:

$$C_{maint} = MTTR * B_m + C_{mat} \quad (3)$$

In addition, the inspection costs are calculated by using Equation 4:

$$C_{insp} = T_{insp} * B_m \quad (4)$$

Average maintenance costs are found by summing the maintenance and inspection costs, and averaging them across the total flight hours for the fleet. Upon completion of the simulation, fleet-wide metrics for cost and time are calculated by summing the data stored by each vehicle and part.

2.4.2.9 Technology Representation

This model has the capability of representing technologies that impact vehicle parts, performance, and base maintenance practices through the use of impact factors or "k-factors". K-factors represent the impact a technology has on different characteristics in the model as a

scaling factor, i.e. a percent change from the baseline. For example, if a new technology is expected to reduce vibrations in the vehicle by five percent, it may be represented by applying a k-factor on the result of the vibration calculation. A k-factor of -0.05 and would result in the following relationship:

$$X_{new} = 0.95X_{old} \quad (5)$$

By using k-factors it is therefore unnecessary to customize the code to incorporate the exact mechanism that resulted in the lower vibrations.

In the model, performance factors include those impacting power, empty weight, figure of merit, lift-to-drag ratio, and vibration magnitude, matching the technology factors available in quantitative performance codes (Ref. 37). Additionally, each part input can be modified to account for the expected impact of a technology on its maintenance parameters. New parts may also be added to change the configuration to reflect the use of a technology. K-factors are set within the model input files on each part type and on the base inputs. Representing multiple technology effects is achieved by externally calculating an overall k-factor for each parameter, and substituting that into the model.

2.4.3 Model Verification

In order to verify the model, a proof-of-concept model instance was created for a fleet of six UH-60M vehicles. This vehicle was chosen as the baseline due to readily available data and its relevance to the research objectives. Vehicle performance figures used in the mission calculation were taken from an NDARC UH-60M model. As stated previously, within the model a vehicle can be represented with as many or as few parts as desired. The model vehicle was built from the parts listed in Table 14 and is flown through the basic mission described in Table 13. These parts and mission were selected to allow for an adequate representation of the UH-60M baseline.

Table 14. Vehicle Components

Forward Airframe	Mission Equipment	Auxiliary Power Unit
Center Airframe	External Supports	Hydraulics
Aft Airframe	Avionics	Fuel System
Tail Pylon	Engine	Flight Controls
Electronics	Main Rotor	Transmission
Landing Gear	Control Rod	Tail Rotor

The simulation was performed by switching maintenance calculations for the vehicle parts between life-limited and AHM. AHM is simulated in the model by initiating maintenance actions based on the part reaching a threshold on its cumulative damage. Additionally, a sweep was made on the mission rate per day.

2.4.3.1 Results

Notional results from the simulation relating to excess availability are shown in Figure 28. The dominant trend of the figure illustrates the inverse relationship between mission rate and excess availability. As more missions are generated, vehicles spend more time on missions and in maintenance, and less time waiting. Switching between life-limited maintenance and AHM has the effect of increasing the excess availability, due to the increased MTBMA.

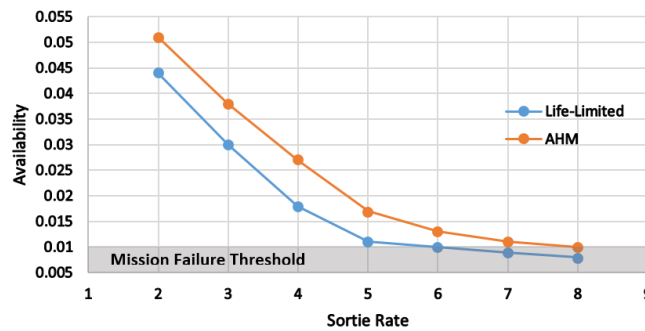


Figure 28. Preliminary Results for Fleet Excess Availability vs. Mission Rate

The inverse trend is expected intuitively and confirmed by the same relationship found analytically by Scott in Reference 22. While the work of Scott focuses on civilian rotorcraft, scheduled flight hours per year and mission rate are both measures of demand, and therefore the same trend is expected. The asymptote observed in Figure 28 is the result of the mission manager aborting missions due to a lack of available vehicles. Vehicles that would have become ready partway through a mission are instead available.

Further analysis of the data showed another trend. As the maintenance calculation is switched to AHM from life-limited, the required MMH/FH for the fleet decreases, as demonstrated in Figure 29.

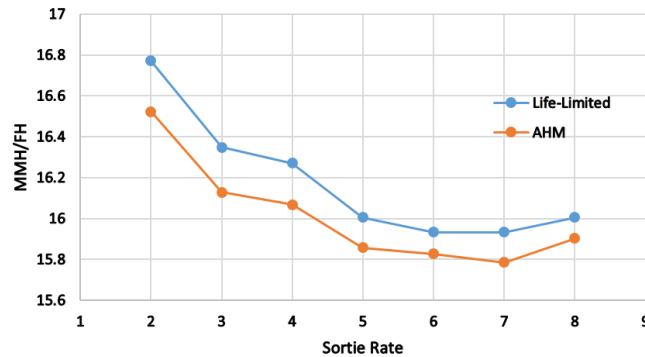


Figure 29. Preliminary Results for Fleet MMH/FH vs. Mission Rate

When the results shown in Figure 28 and Figure 29 are evaluated together, it can be seen that when utilizing AHM the excess availability is increased while simultaneously decreasing MMH/FH.

2.4.3.2 Concluding Remarks

The DES model, as executed in the proof of concept, demonstrated results that could not be quantified from performance-based tools such as NDARC. A test case using the DES model demonstrated the ability to assess a technology that impacts non-performance attributes, giving a more complete picture of the capability space for advanced rotorcraft.

2.4.4 Critical Questions and Limitations

While preparing the model for presentation at AHS Forum 72, a number of limitations were identified that needed to be addressed going forward. The first limitation identified had to do with the Mission Manager and how the vehicle is passed to maintenance. Prior to sending a vehicle on a sortie, the Mission Manager performs a preflight inspection. During preflight inspection if there are any damages then the vehicle is passed to the Maintenance Manager. However, the Mission Manager also assesses whether the mission will cause a failure and in anticipation of this will send the vehicle to preventative maintenance prior to failure. The critical result of this is that the vehicle never suffers a mission critical failure.

The next limitation identified had to do with the randomness of the model. In order to evaluate the RAM metrics identified in the model description, the model needs to iterate on a stochastic process and average the results. This is currently not the case as the model takes in fixed point values for all inputs and as a result the output is inherently deterministic.

The last limitation identified prior to presenting was that the model doesn't capture several of the Future Vertical Lift's desired metrics. The model does not currently report on the Maintenance Free Operating Period (MFOP) and False Removal Rate (FRR) for the vehicle.

In addition to the limitations identified prior to presenting the model at AHS Forum 72, the feedback from the audience identified several critical questions that should be addressed. Firstly, the method for aging the parts is currently modeled after a technique presented in the *Principles of Helicopter Aerodynamics* text by Leishman. The referenced vibration mapping technique used to age the vehicle in the current version of the model is dated, circa 1970s, and is likely inaccurate for this era of vehicles. A more accurate form of aging the vehicle is necessary if the outputs are ever to be validated. Secondly, not all components are critical for each mission phase and in addition to that not all components are safety critical some are just mission critical. In other words, while a component may be critical for both the safety of the vehicle and the success of the mission, another less critical component may be only mission critical, having no effect on the safety of the vehicle. Expanding this question, consideration should be given to how the critical components vary with respect to the mission phase.

The following table, Table 15, breaks down each aforementioned question or limitation and how it is being addressed.

Table 15: Operations Model Limitations

Question/Limitation	Addressed in FY16	Not Addressed
1. With preflight inspection and failure anticipation the vehicle never suffers a mission critical failure	Corrected with IPLE operations model	
2. The model is inherently deterministic, there is no stochastic process representing what is realistically happening	IPLE model is built on stochastic inputs, new Maintenance Manager takes stochastic input for MTTR, Cost, and Shop Status	

3. Maintenance Free Operating Period (MFOP) and False Removal Rate (FRR) are not considered	MFOP capability added during IPLE merge	FRR could be considered, no framework exists currently
4. The Leishman vibration mapping is outdated, circa 1970s, and is likely inaccurate for this era of vehicles	By using component failure rate data, there is no need for vibration mapping	
5. There is no consideration given to mission critical and safety critical components being represented in the operational cycle nor how these vary between mission phases	The IPLE model is built on fault trees input for each unique mission phase. One for mission critical and one for safety critical.	
6. Plan for validating the model		There is currently no plan to address this as doing so requires field data

2.4.5 Improved Model with Phased-Mission Simulation

To study the Reliability, Availability, and Maintainability, an integrated simulation environment was developed, which is illustrated in Figure 30. Detailed description of the various steps in the simulation are described in the following sub-sections. This discrete-event simulation program is designed to be modular and represent the fact that each operational mission-phase has a different set of mission/safety critical systems as well as systems in use. The simulation is performed for a single vehicle; the simulation assumes a certain number of flight hours the vehicle will be in operation for and once this number is reached, one monte-carlo run is completed. A similar full operation cycle is run multiple times to obtain the long-term steady-state results for the various simulation metrics, such as overall mean up-time and down-time, etc. The simulation requires a typical mission to be inputted with its different phases and time spent in each phase, such as Hover, Cruise, etc. Each phase has a set of mission-critical systems, modeled as event trees (this is described in section 2.4.5.1). These mission critical systems are encoded through a fault-tree: each

mission phase has its own unique event-tree. Similarly, each mission phase will have its own safety critical system list (fault-tree). The simulation input file has a table of information with mission phases, the mission and safety critical fault-trees, system/component reliabilities, etc. Each phase also has a list of systems/components that ‘age’ (this is described in section 2.4.5.2).

The simulation uses random variates to model the different component reliabilities for simulating system failures and keeps track of component-age, and maintenance actions can be scheduled to reset the age of failed and repaired systems, accordingly. This feature adds stochastic variability to the simulation, addressing the deterministic issue. When a mission-critical event occurs in the simulation, the rest of the mission is aborted and the vehicle is sent into maintenance. When the vehicle goes into maintenance, the maintenance manager computes the down-time based on the Mean Time To Repair (MTTR), Administrative Delay Time (ADT), and Logistics Delay Time (LDT), and maintenance costs—these are all currently modeled with stochastic variability as well.

The simulation can be run in different configurations to either estimate Operational Availability* (A_o), System Safety, or Maintenance Free Operating Period (MFOP), etc. The focus of the current research has been on predicting Operational Availability and O&S cost.

*Operational Availability is defined as the ratio of ‘Uptime’ to the sum of ‘Uptime and Downtime’.

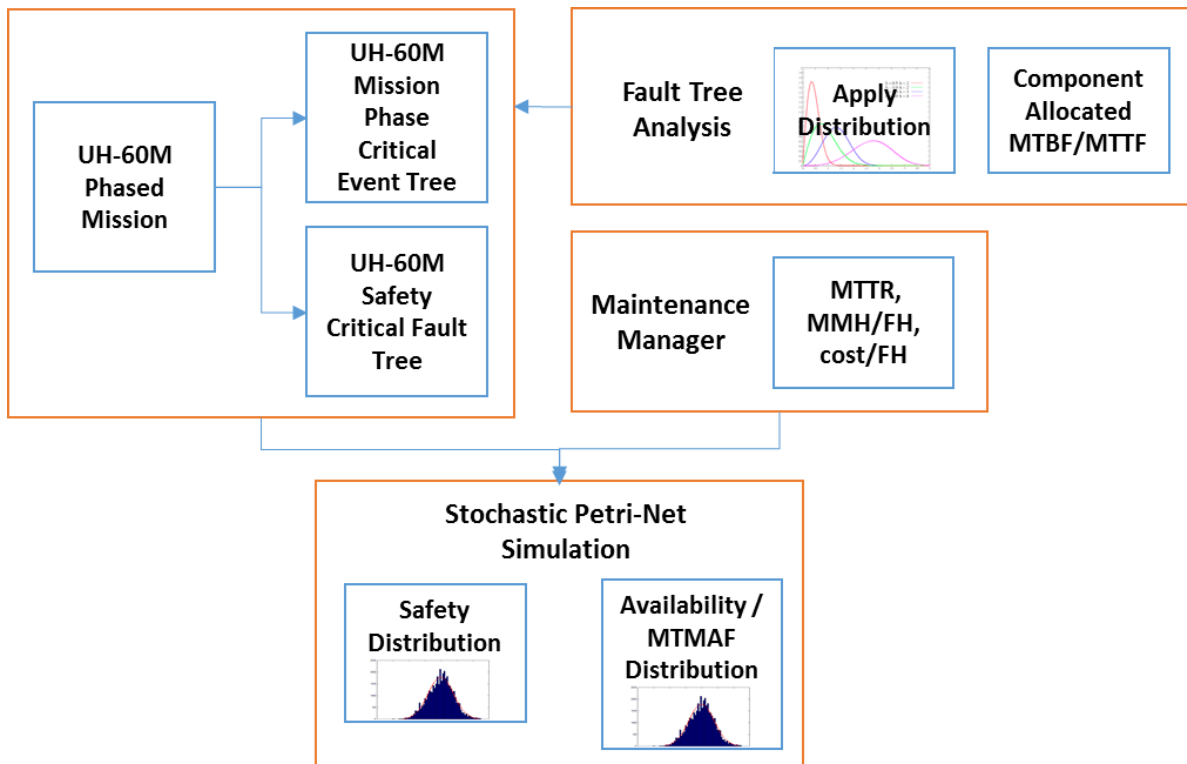


Figure 30. Integrated Discrete Event Simulation Environment

2.4.5.1 Mission Critical Event Tree

A mission critical event tree is similar to a fault tree structure and based on what mission-phase the vehicle is in, a series of mission-critical events can be modeled. An event tree automatically generated in Simulink is shown in Figure 33. This event tree is created in excel, as shown in Figure 32. This process requires some a-priori knowledge of the system architecture and how the system behaves in different missions. In conceptual design stages this process requires the usage of some historical information of system architecture and failure information, as the design process progresses and more information is made available, this should be updated.

2.4.5.2 System Ageing

A unique feature of this simulation model is the ability to treat certain systems/components as dormant during certain mission phases. This means that these systems will have their own ageing clock that will allow ageing only in mission phases that utilize this system. For example: the landing gear will not age during cruise mission phase. This aspect of the program also allows for resetting the age of repairs/replaced components without affecting other systems/components. This is another reason for breaking down the systems to the component level, otherwise the simulation will erroneously reset the age of the top-level system instead of the repaired/replaced component. These features are extremely important to accurately simulate the actual operation and functioning of the vehicle. For these reasons, the phased-mission and ageing component form of simulation is more accurate than a general overall system petri-net.

2.4.5.3 Input Process

Efforts have been taken to improve the usability of the previously-developed model by increasing input scalability, implementing input error-checking capabilities, and improving the Excel input user interface. A flow-chart of the process for input and error-checking is shown in Figure 31.

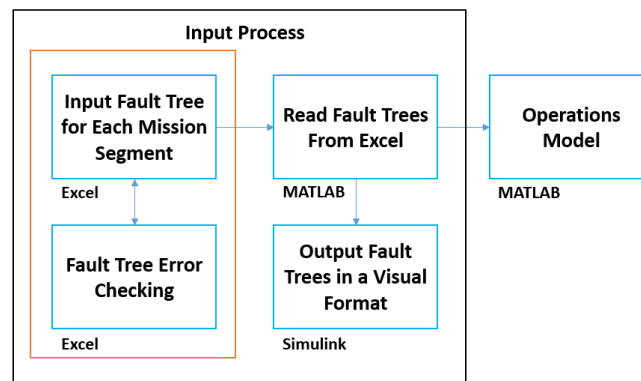


Figure 31. Input Data Flow

	Top Cell Only, Too many systems specified in that column		Known Failure Distribution	-1
	Whole Column = Not Enough systems specified in that column		'OR' Statement	0
	Number of additional cells indicates number of missing systems		'AND' Statement	No leading value
		Check Fault Tree	I Fixed It!	
Name	Number	Time (hrs)	Aged Systems	
Cruise Out	4	0.983333333	[1,2,3,4,5,6,7,8,9,10,11,12,13,15,18,19,20,21,22,23,24,25,26,27,32,33,34,35]	
Mission Go	0,0			
Mission Critical	0,G1,G2,G3,G4,G5,G6,G7	0,G8,G9,G10,23,35	0,13,10,9	-1
		0,6,5,7,8	0,1,10,9	-1
		0,11,19,20,21,32,35	0,2,15,9,3	-1
		0,22,12	-1	-1
		0,24,25,26,27	-1	-1
		3,4	-1	-1
		0,34,18,33	-1	-1
			-1	-1
			-1	-1
			-1	-1
			-1	-1
			-1	-1
			-1	-1
			-1	-1
			-1	-1
			-1	-1
			-1	-1
			-1	-1
			-1	-1
			-1	-1
			-1	-1
			-1	-1
			-1	-1
			-1	-1
Safety Critical	0,0			

Fault trees are represented using a top-down approach looking left to right in Figure 32. Cells corresponds to either an OR gate (a cell with a leading zero) and corresponding inputs for the gate, an AND gate (a cell with no leading zero) and corresponding inputs for the gate, or a -1 that tells the fault-tree reading script to use a failure distribution for the component as defined in the 'Systems' tab. Any 'G' represents an intermediate gate and is used for additional system decomposition and may correspond to either an AND or an OR gate. As systems or intermediate gates are added, additional definition is provided in the next column. A column is organized by reading left to right in the first through the last cells of the previous row. As an example, look at the third column of Figure 32. In the first row, the entry is '0,G8,G9,G10,23,25'. This is an OR gate with 3 intermediate gates: G8,

G9, and G10; and 2 specific systems defined: 23 and 35. In the next column the three gates are defined, which all happen to be additional OR gates, and the two systems have -1 values in the next column that tell the program to look for a failure distribution for those components. Using this approach, the modeling philosophy is flexible and scalable and may include any size fault tree or number of components.

Since the fault trees are a critical component of the operations analysis, it is important that the fault trees used in the operations analysis match user expectations. The simplest way to verify that the fault trees entered into the Excel sheet are consistent with user expectations is by visual inspection of the fault tree. The fault trees, as represented in Excel, are read into the operations model as a cell array using a MATLAB script. This cell array is used to automatically create a visual representation of the fault trees in Simulink. Because no features exist to rearrange blocks for aesthetics and a general formulation is difficult to generate, connections between blocks may cross over other blocks at times. An automatically generated fault tree corresponding to the Excel input shown in Figure 32 is shown in Figure 33 below. Note that this diagram is intended to be a second-level of error checking to ensure that the fault tree is consistent with the intent of the user.

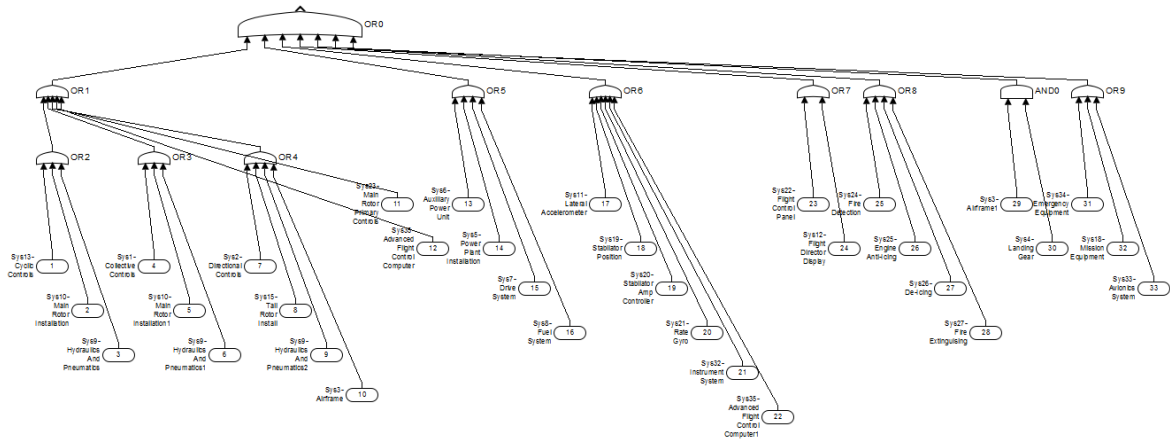


Figure 33. Simulink Fault Tree Diagram Automatically Generated for Visual Error Checking

2.4.5.4 Preliminary Results

The following figures are simulation results obtained by simulating 1500 flight hours for a notional utility mission with some nominal failure/repair rates, with only one non-unique mission-critical event tree (shown in Figure 33). The monte-carlo runs are set to terminate when the coefficient of variation between runs reaches a certain threshold. These results are presented to demonstrate capability of the operations model and are preliminary results that are not fully-indicative of an actual vehicle.

The raw data for time between mission affecting failures, for all simulation runs is shown in Figure 34. This figure shows that for no instance of the simulation, was the vehicle able to perform over 12 hours of operation without requiring to abort mission due to some component failure. The inverse cumulative distributive function for Operational Availability (A_o) is shown in Figure 35, and given the aforementioned limitations of this simulation, the results are narrowly distributed between 39.5% and 43.5%. Similarly, the Mean Time Between Mission Affecting Failures (MTBMAF) is shown in Figure 36; this is raw data aggregated for each monte-carlo run. According to this plot, the MTBMAF for this vehicle will neither be greater than 3.1 hours nor less than 2.75 hours. The simulation is also built with the capability to identify mission abort influencing components, and this is plotted as histogram shown in Figure 37. Since the simulation uses aggregated systems, some systems such as 'Airframe' and 'Main Rotor Installation' show an unusually high failure frequency—these results can be made more accurate and realistic by including more descriptive mission critical event trees for the different phases.

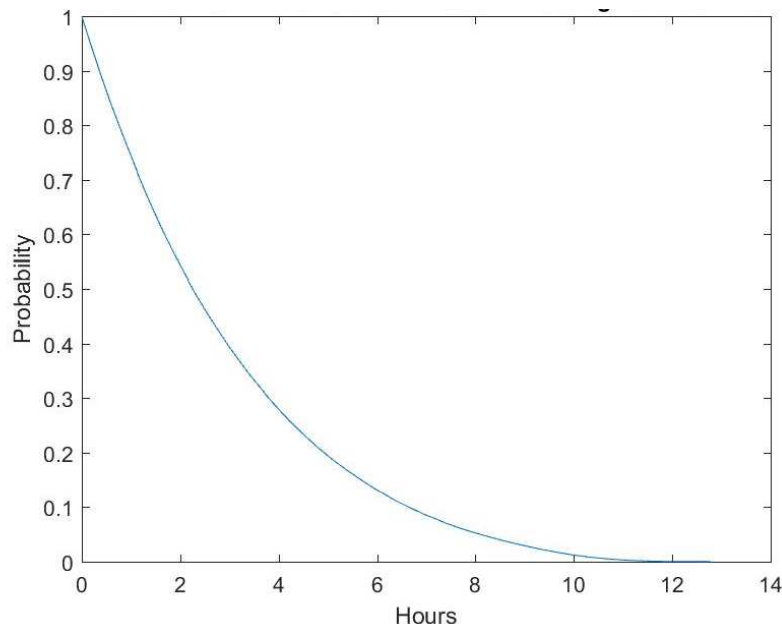


Figure 34. Raw Data CDF of Time Between Mission Affecting Failures

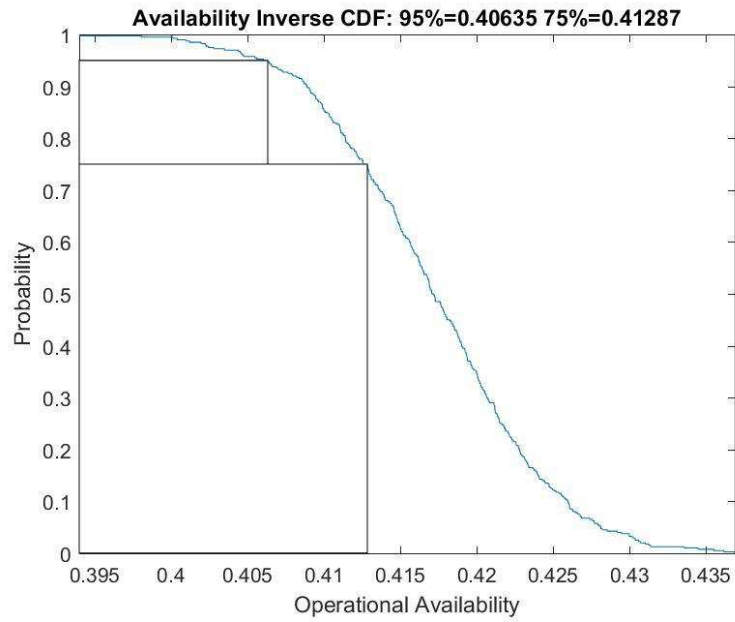


Figure 35. Inverse CDF of Operational Availability

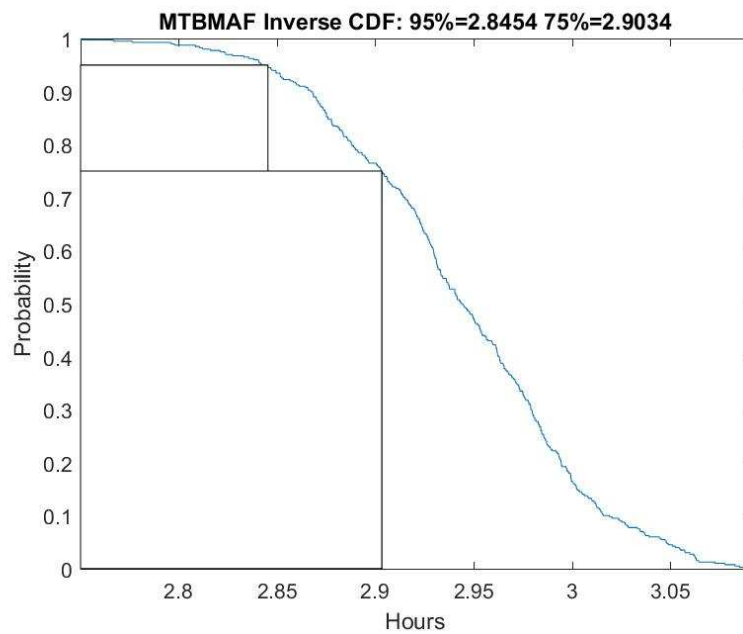


Figure 36. Inverse CDF of Mean Time Between Mission Affecting Failures

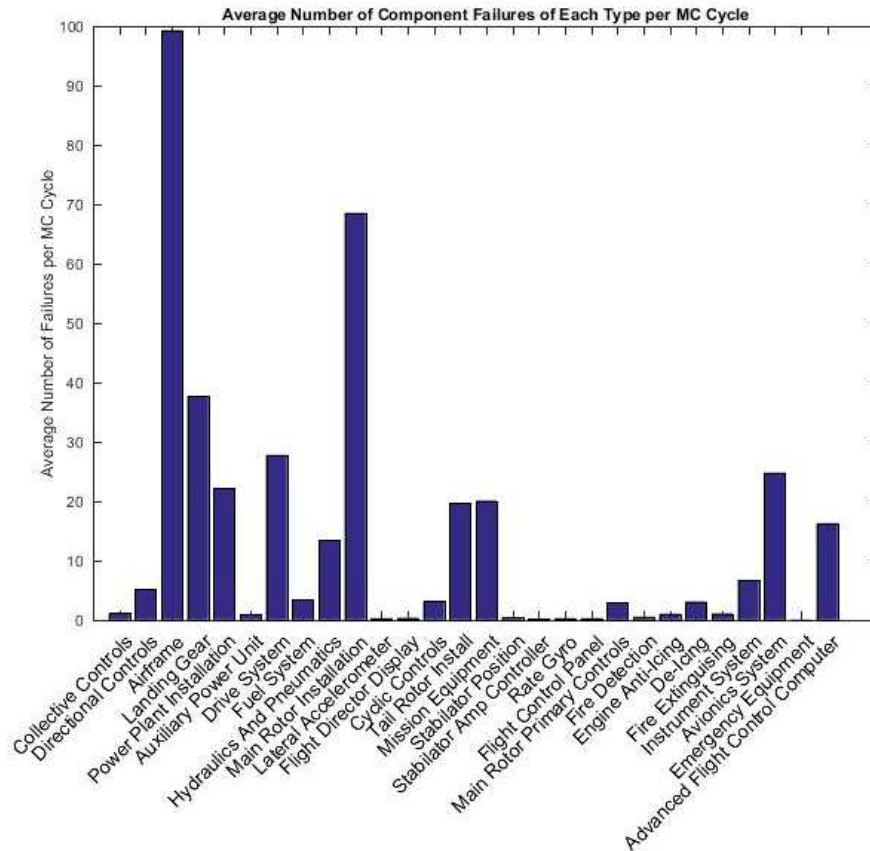


Figure 37. Histogram of System/Component Failure Frequency

2.4.6 Future Work

The team will continue to make enhancements to this simulation environment so it is able to better predict the RAM metrics of interest. Some areas that are currently being/potentially be pursued for FY17 are:

1. System and component redundancy: adding this feature to the model will help study component redundancy trade-off between Availability and Capability.
2. Populating mission-phase specific event trees and component ageing information. The model currently does not have this information and more work needs to be done in this area to be able to predict RAM data accurately.
3. Adding safety critical information through Function Hazard Assessments (FHA) and Failure Mode Effects and Criticality Analysis (FMECA) would add capability to study system safety.
4. Adding fidelity to maintenance manager: the current model needs to be enhanced to better predict Mean Down Time (MDT), which includes repair time, logistics delay time, and administrative delay time.
5. Exploring maintenance paradigms. Different maintenance paradigms could be explored using this simulation to study how RAM/cost is affected in the different cases. Dynamically scheduling maintenance actions on certain parts is an example. The current model has a single level

maintenance paradigm in that all maintenance occurs at a single hub. Expanding this to a two level paradigm where more exhaustive maintenance occurs at the OEM or maintenance depot would add a more thorough representation of O&S costs and downtime.

6. Improving O&S cost prediction. Incorporating more data on component cost and how maintenance man-hours can be modeled will give better prediction of O&S cost.

2.4.7 Combat Survivability Model

The addition of a combat survivability model to the current operations simulation is targeted at allowing the evaluation of the combat effectiveness of different concepts. For utility-class rotorcraft, the focus of the current work, combat effectiveness can be assessed simply as surviving. Aircraft combat survivability is defined by R. Ball in *The Fundamentals of Aircraft Combat Survivability Analysis and Design, Second Edition* as the capability of an aircraft to avoid or withstand a man-made hostile environment (Ball, 2003). This can be measured as the probability the aircraft survives an encounter (combat) with that environment:

$$P_S = 1 - P_K = 1 - P_H P_{K|H}$$

$$Survivability = 1 - Killability = 1 - Susceptibility * Vulnerability$$

Where susceptibility is the inability of an aircraft to avoid being hit by the environment and vulnerability is the inability of an aircraft to withstand that hit. It is logical to then conclude that any technology or concept which reduces the vulnerability and susceptibility of the aircraft to the combat environment will increase the aircraft survivability and ultimately reduce O&S costs.

Research into the typical threat environments encountered by utility-class rotorcraft by mission is detailed in Table 16. It can be seen that, unlike fixed wing aircraft, slow moving, noisy and relatively soft vehicles, such as rotorcraft, operating in close proximity to the ground and hostile ground forces are exposed to a wide range of threats. While some discrepancies occur, such as the presence of Surface-to-Air Missiles (SAMs), for the desired fidelity of the model it is sufficient to approximate the threat environment to that of the Air Support and Battlefield Insertion/Extraction missions.

Table 16: Threat Environment by Mission

	Battlefield Insertion/ Extraction	Urban Insertion/ Extraction	Special Operations	Humanitarian Aid	Air Support	Search and Rescue (SAR)
Small Arms	X	X	X	X	X	X
Machine Guns	X	X	X	X	X	X
Self Propelled Anti- Aircraft Gun (SPAAG)/Semi- Mobile AAA	X		X		X	X
Mortars	X	X	X	X	X	X
Rocket Propelled Grenade (RPG)	X	X	X	X	X	X
Artillery	X	X	X		X	X
Man Portable Air Defense System (MANPAD)	X	X	X	X	X	X
Surface-to-Air Missile (SAM)			X			X

Model Assumptions

A number of assumptions are made to simplify the model while still maintaining the desired level of fidelity. Most notably the detectability of the vehicle is assumed to be 100%. This assumption is made due to utility-class rotorcraft having very little in the way of EO/IR signature reduction and noise control in addition to flying low and slow. Another assumption, as mentioned previously, is given the consistency of rotorcraft threat environments it is sufficient to approximate the threat environment to be constant, corresponding to that of the Air Support and Battlefield Insertion/Extraction missions. Along the same line, given that the vehicle being modeled is utility-class, it is assumed that the vehicle has no offensive capabilities to be modeled. Lastly, to simplify the analysis, a constant speed and altitude corresponding with the cruise mission phase will be used.

UH-60M Use Case

Once the combat survivability methodology is complete, a case study will be done for the UH-60M. This effort aligns with the use case from the CATE work and will add a more thorough O&S analysis. To accomplish this a few issues must first be addressed: component specific susceptibility and vulnerability require some knowledge of the component's exposure and location within the vehicle, assumptions can be made for each threat's kill-chain associated with P_H but data is needed to verify the validity of those assumptions, and the best distribution for representing the chance of threat occurrence must be determined.

2.5 Develop Case Study with CATE around the UH-60 Blackhawk

This section details the approach to use the CATE environment on a specific vehicle, the UH-60. First a new method for calibrating the UH-60 vehicle has been used. From the calibrated vehicle, technologies were implemented to represent the upgrades and to investigate possible future configurations.

2.5.1 Calibration

The NDARC files have been calibrated using a new procedure. The Figure 38 and Figure 39 illustrate the difference between the previous year's calibration method and the updated calibration. Some additional details on the previous year's approach can be found in the previous yearly reports. The objective is to get the correct NDARC files describing the RPTM engine parameters, aircraft weight calibration factors, rotor induced and profile power and airframe model. The derived NDARC files will be used as the vehicle baseline used in the other parts of the tool. The calibration process is made in a three step process, going from one loop to another, starting inward: calibrate geometry, calibrate the power required and fuel flow and calibrate the weights. Calibrated geometry gets flat plate drag and layout corrected, which will influence power required. Power required influences fuel flow, and should be calibrated in that order. However, power available is independent, and can be calibrated on its own. Both can influence weight, so component weights should be calibrated last. The data for the UH-60A model is taken from a variety of sources. The NDARC script is modified from a SMR example packaged with the NDARC user training files. Geometry for the UH-60L is derived using dimensions from the UH-60A math model [10] and the UH-60A/L operator's manual. There are no external differences between the UH-60A and UH-60L, so it is assumed that the UH-60A math model dimensions apply.

Empty weight is calibrated to the weight information for a manufactured UH-60L from a Sikorsky weight statement for the 1571st production helicopter using technology factors [11]. Power required and available data and fuel flow data are derived from the UH-60A/L Operator's Manual. The NDARC calculations of power required are calibrated to the operator's manual data using a two-step process. This calibration is more complex than calibrating the geometry and empty weight due to the large number of parameters (around 60) that could be used to modify power required estimations. Thus, the first step is to reduce the amount of variables using statistical variable screening to identify which parameters contribute the most to the variability of power required in hover and in forward flight. The second step uses an optimization algorithm to find settings for the parameters identified in step one that most

accurately represent the performance data from the operator's manual. Any settings identified as not significant to the variability of power required are defaulted to the SMR example setting packaged in the training files. The multi-objective genetic algorithm is used to minimize the two objectives given below by varying the parameters identified in step one. This algorithm is chosen because it handles non-linear, discontinuous computation models and performs multi-objective optimization. For simplicity, the following two objectives are used.

1. Minimization of Root Mean Squared Error (RMSE) of power required to hover for gross weights between 12,000 lb and 21,000 lb, and at sea level standard (SLS) and 4000 ft, 95 °F
2. Minimization of RMSE of power required in forward flight for set of forward speeds ranging from 0 to 155 kts at gross weights of 16,000 lb and 18,000 lb, and at SLS and 4000 ft, 95 °F

Calibration points are gathered by digitizing performance charts from the Operator's Manual. Figure 40 is a sample image showing where points were taken for power required and fuel flow data.

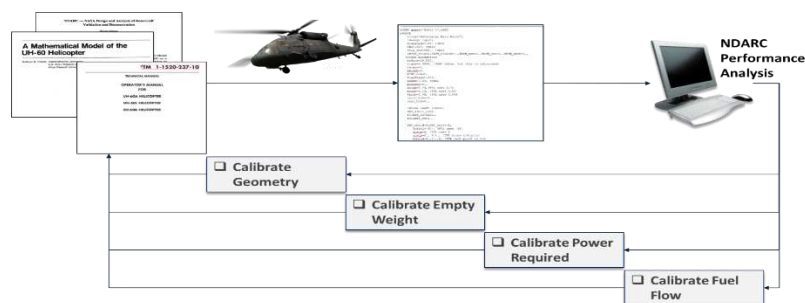


Figure 38 Previous years calibration method

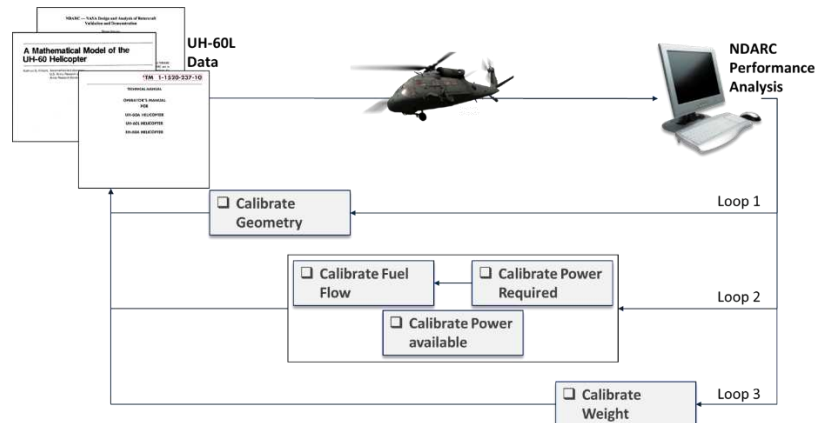


Figure 39 Updated calibration method

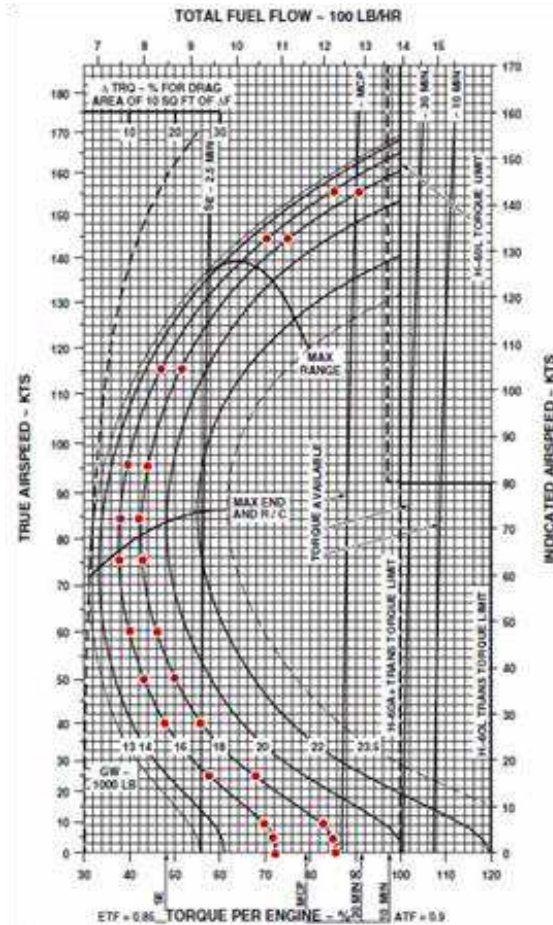


Figure 40. Sample Plot Indicating Pulled Data Points for Power Required and Fuel Flow

2.5.2 NDARC Engine Upgrade Approach: Power Available with and without Calibration

2.5.2.1 Introduction

In order to better understand how to model upgrades using technologies, within the CATE environment, the UH-60A to UH-60L upgrade was used. The UH-60L maintains the same geometric features as the UH-60A but includes an upgraded engine and improved high-durability gearbox. The purpose of this exercise is to focus on the engine upgrade, modeling the increase in Power Available and change in Empty Weight. The UH-60L is equipped with two General Electric T700-GE-701C turboshaft engines, whereas the UH-60A is equipped with two General Electric T700-GE-701 turboshaft engines. Table 17 below compares the two engines.

Table 17: UH-60A/L Engine Comparison

	UH-60A	UH-60L
Engine	GE T700-GE-701	GE T700-GE-701C
Rated Horsepower (IRP)	1,560 shp	1,800 shp

2.5.2.2 Scenarios

Two scenarios were identified as ways to model the engine upgrade in NDARC. The scenarios laid out here are different from the full calibration procedure. These scenarios assume that the technology (i.e. the engine) can be modeled within CATE environment using technology factors rather than by a complete NDARC Referred Parameter Turboshaft Engine Model (RPTM). To simplify the process, only Power Available was considered. The model's calibration figure of merit is the Root Mean Square of Errors (RMSE), which is calculated as the difference between the NDARC prediction and data published in the UH-60L Operator's Manual for Maximum Continuous Power (MCP), Intermediate Rated Power (IRP), and One Engine Inoperative (OEI). The Power Curves give Power Available values for various flight conditions (i.e. velocity, altitude, temperature). To study the effects of the engine improvements, a calibrated UH-60A model was used as the baseline. The scenarios are as follows:

1. Change a few NDARC parameters to see impacts on RMSE's
2. Replicate full calibration process but with fewer NDARC parameters

Scenario 1

This scenario involves changing certain NDARC parameters based on known information about the engine in order to see the impacts on the RMSE's. The following parameters (listed in Table 18) were identified based on the fact that they would be known about an engine even if it hasn't been developed yet. Table 18 also includes both the UH-60A and UH-60L values for these parameters.

Table 18: Scenario 1 NDARC Parameters

NDARC Parameter	Description	UH-60A	UH-60L
Peng	SLS Engine Power	1560	1800
Plimit_es	Engine Shaft Power Limit	2828	3400
Plimit_ds	Drive System Power Limit	2828	3400

Utilizing ModelCenter, the UH-60A aircraft file was changed to include the UH-60L parameters from Table 18 without changing any other variables and the RMSE's were calculated. Table 19 summarizes the RMSE results for Scenario 1.

Table 19: RMSE Results for Scenario 1

Engine Operating Condition	RMSE (shp)
MCP	93.191
IRP	84.596
OEI	64.653

It is important to note that the errors in Table 19 remain fairly small compared to the expected shaft horsepower (~1800). Figure 41 illustrates an example of the error in MCP for each atmospheric operating condition for Scenario 1.

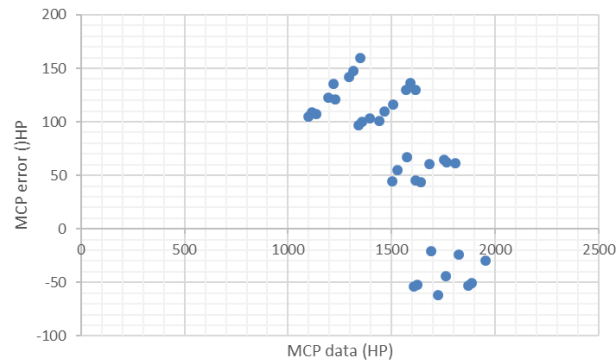


Figure 41. MCP Data vs. MCP RMSE for Scenario 1

Each point in Figure 41 compares the power available RMSE for each different flight condition (i.e. altitude, velocity, and temperature) to the actual power available for that flight condition given by the operator's manual. This figure shows that for many different flight conditions the errors are generally small compared to the actual power available.

Scenario 2

This scenario seeks to replicate the full calibration process but by only varying a smaller number of NDARC parameters. Within NDARC, Power Available is modeled with polynomial expressions. The full calibration

process varies all the coefficients of these empirical equations in order to minimize the RMSE for MCP, IRP, and OEI power available. However, for this scenario this is not the case. The parameters used are shown in Table 20. It is important to note that they were chosen due to the fact that they are important engine parameters that could be used to model simple technology improvements with. The parameter values used in Scenario 1 were used here as well.

Table 20: NDARC Parameters to be Varied for Scenario 2

NDARC Parameter	Parameter Description
Nspec_tech	Specification Turbine Speed
ENG_SPOC_tech	Specific Power at MCP
fPloss_xmsn	Gear Box Loss
eta_d	Engine Inlet Efficiency
fPloss_inlet	Engine Inlet Loss
fPloss_exh	Engine Exhaust Loss

After varying these parameters between certain ranges, it was seen that this scenario resulted unsuccessful. There weren't any improvements to the MCP, IRP, or OEI RMSE's.

2.5.2.3 Conclusions and Lessons Learned

Taking all of these scenarios into consideration, one can conclude that Scenario 1 best models the UH-60A to UH-60L engine upgrade with regards to power available. It uses actual engine information that will more than likely be known to the decision maker rather than guestimates and doesn't include parameters that will require "tweaking" in order to match to actual engine data that may not be available.

Throughout this process, researchers identified a number of lessons that have been learned. First and foremost, there is a need for a way to improve engine modeling within the CATE environment. These scenarios rely heavily on the power available regressions within NDARC that are used to model the engine that are fitted to power curves from the operator's manual. This makes evaluating technologies difficult without having the power curves readily available. Also, currently in the CATE environment, the sizing surrogate engine parameters are limited to technology factors on Accessory Power, SFC, and Engine Weight alone.

With these lessons, researchers have been able to suggest a few possible solutions. The first solution would be to utilize higher fidelity engine modeling with tools such as NPSS. This would allow a decision maker to tweak parameters related to specific engine technologies within the engine rather than the engine as a whole. This will still require curve fitting the results of the higher fidelity model to NDARC parameters, similar to what is being performed in the NDARC rotor spreadsheet. Another possible solution would be to explore other engine modeling methods within NDARC. After some investigation into how NDARC can model an engine, it was discovered that the turboshaft engine can be modeled with a table lookup rather than the Referred Parameter Turboshaft Engine Model. Though this may be a very good approach for existing vehicles where there is a wealth of data, this would not be a trivial approach for forecasting future engines or engine technologies.

2.5.3 UH-60M Upgrade and Future Technologies

The following section details the modeling of the UH-60M and the ITEP engine within CATE. CATE modeling environment is based on a sizing task: given some sizing condition and mission parameters, some design parameters and given some technology calibration factors affecting weight, drag and engine performance, a vehicle is sized and the characteristics are output. The CATE environment is an Excel-based implementation of regressions of the sizing task. Table 21 shows the sizing input and output of CATE

Table 21 CATE input and output variables

Input parameters			Output Parameter
Sizing Condition & Mission Parameters		Eng sizing alt (ft) Eng sizing temp (F) VROC VFWD hover time cruise time Wcrew ft hover time ft cruise time	Design Gross Weight (Structural Design Gross Weight Empty Weight Fuel Weight Operating Weight Useful Load Propulsion Group Weight Empennage Weight Engine System Weight Fuselage Group Weight Rotor Group Weight Structure Weight
			Main Rotor Radius Main Rotor Solidity Aircraft Drag Fuselage Drag Main Rotor Hub Drag Main Rotor Pylon Drag
Tech Factors	Design Parameters	Blade Loading disk load location cg Vtip of Main Rotor	Drive System Limit CRP (per engine) MRP (per engine) TOP (per engine) IRP (per engine) MCP (per engine) MCP SLS sfc
	Tech Factors (Drag)	Fuselage CD CD ff CD V fus CD MR hub CD MR pylon CD TR hub tech drag MR tech drag TR	
	Tech Factors (Weight)	Engine TECH gearbox TECH_rs TECH_ds Fuselage Body Rotor Blade Rotor Control RWfc_b Rotor controlRWfc_mb Rotor Control RWhyd	
	Engine	Engine.Pacc_0 Engine.SP0C_tech Engine.sfc0C_tech	

Among the technologies affecting the performance of UH-60M, it has an upgrade engine (GE-710D turboshaft engine) and Wide Chord Blades (WCB). In the previous year, the UH-60M has been modeled in the sizing environment. The UH-60L vehicle parameters were changed to represent the technology:

- Increasing VROC and maximum speed specifications to increase the power of the installed engine.
- Changing the engine technology factor will account for the technology on the T700-701D that allowed for increased power without increased size.
- Changing the blade loading and the rotor blade factor will account for the major changes of the WCB.

The parameters affected by the upgrades relative to the UH-60L are illustrated in Table 22.

Table 22 UH-60M upgrades modeling assumptions, compared to UH-60L

Upgrade	Projected impact		
Wide Chord blade	CWs : -9%	TECH_blade -12.1%	
701D engine	TECH_eng -3.6%		

It was noted that the increases in size due to the significant increases in payload and crew weight causing the vehicle to become larger overall due to sizing analysis. Consequently, an alternate approach is proposed in the following section. The approach uses an optimization routine to converge on the design inputs that lead to the predicted design output. In other words, the objective is to output the mission capabilities linked to new technologies without a change in vehicle size.

For a change in engine performance, the optimization problems is posed as:

Minimize :

$$n_1(\text{predicted power} - \text{modeled power})^2 + n_2(\text{predicted TOGW} - \text{modeled TOGW})^2$$

where 'n's are scaling factors (typically one over the nominal value of the associated design variable)

With respect to: VFWD, cruise time The optimizer was the GRG nonlinear internal excel Solver and the regressions already present in CATE were used for the process.

For the proposed UH-60M, analysis, only the engine is upgraded, to keep the weight bookkeeping easier to understand. Note that it was noted in the previous year that the WCB had limited impact on the vehicle performance.

First, the engine weight calibration is changed from the nominal value of 1.43 to 1.397 (reduction of 3% in engine weight) to account for the increase in power without the increase in engine weight. Then the

optimization routine is performed: the cruise time and forward velocity are changed to return the expected engine power without changing the vehicle weight.

The results are illustrated in the Table 23.

Table 23. Engine upgrade in CATE results: change in forward velocity

Parameter	UH-60L (CATE)	UH-60M (only engine) CATE
V_{FWD} (KTAS)	148.5	151.3
Cruise time (min)	83.9	78.9
Gross weight (lb)	18,601	18,602
MCP (hp)	1851	1906
Rotor radius (ft)	28.46	28.46

The results show that the engine upgrade allows the vehicle to fly faster with a more powerful engine without introducing changes in vehicle weight and size. The design cruise time is reduced by 5 minutes due to the fact that the cruise is at higher speed. This technique allows to isolate specific performance characteristics that are affected by an upgrade without a complete re-design of the vehicle. The same analysis can be performed by replacing the forward velocity by a change in VROC, and these results are shown in Table 24. In this case, the design vertical rate of climb is much higher, as expected, as a result of a more powerful engine.

Table 24. Engine upgrade in CATE results: change in VROC

Parameter	UH-60L (CATE)	UH-60M (only engine upgraded) CATE
VROC	416	922
Cruise time (min)	83.9	80.89
Gross weight (lb)	18,601	18,602
MCP (hp)	1851	1906
Rotor radius	28.46	28.46

The same process was applied to evaluate the impact of installing the ITEP engine on the UH-60. Unfortunately, the bounds of the surrogate models on the VROC and VFWD did not allow to have the expected power (3000hp per engine). However, the proposed process is similar to the upgraded engine exposed in the previous paragraphs: expected technology factors on specific fuel consumption and engine weight calibration factors are changed in the sizing tab. After, the optimization is executed on the mission parameters in order to match both the expected power and the vehicle weight.

2.6 Survey of Technology Forecasting Techniques for Complex Systems

Complex system design and assessment is a challenging task exasperated by the need to forecast nascent technology in system evaluation. Proper technology forecasting technique selection will assist decision-makers to understand the risks involved in the integration of emerging technology into existing or new complex system developments. A research summary found in the Appendix surveys the field of technology forecasting using both previous technology forecasting survey results and text mining on academic literature to identify 60 unique technology forecasting methodologies and associated variations. The literature for the technologies is reviewed to place the technique into a family, describe whether it was quantitative or qualitative, indicate whether it could be used for explorative or normative forecasting, rate 12 criteria, and characterize the expected results of the technique. A technology forecasting taxonomy is created from these results. This taxonomy can be used to guide the designer or decision maker to select the most appropriate technique based on the purpose of a forecasting exercise, the characteristics of the technology to be forecasted, and the amount of effort and resources that can be expended for the exercise.

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4 Appendix

4.1 Calibration Parameters

The variables used in the calibration are illustrated in the following table

Category	Parameter	Definition
	Peng	
Weight	TECH_blade	blade weight technology factor
	TECH_hub	hub and hinge weight technology factor
	TECH_rsupt	rotor support weight technology factor
	TECH_rfold	blade fold weight technology factor
	TECH_tr	tail rotor weight (group weight) technology factor
	TECH_tail	tail weight technology factor
	TECH_body	basic body weight technoloy factor
	TECH_crash	body crashworthiness weight technology factor
	TECH_LG	basic landing gear weight technology factor
	TECH_LGcrash	crashworthiness weight technology factor
	TECH_cowl	engine cowling weight technology factor
	TECH_supt	engine support structure weight technology factor
	TECH_air	air induction system weight technology factor
	TECH_eng	engine weight technology factor
	TECH_exh	exhaust system weight technology factor
	TECH_acc	engine accessories weight technology factor
	TECH_plumb	fuel system plumbing weight technology factor
	TECH_tank	fuel tank weight technology factor
	TECH_gb	gear box weight technology factor
	TECH_rs	rotor shaft weight technology factor
	TECH_ds	drive shaft weight technology factor (aka transmission drive)
	TECH_RWfc_b	boosted rotary wing flight control weight technology factor
	TECH_RWfc_mb	control boost mechanisms rotary wing flight control weight technology factor
	TECH_RWfc_nb	non-boosted rotary wing flight control weight technology factor
	TECH_FWfc_nb	non-boosted fixed wing flight control weight technology factor
	TECH_RWhyd	rotary wing flight control hydraulics weight technology factor
	TECH_Dielect	anti-icing electrical system weight technology factor
	TECH_DIsys	anti-ice system weight technology factor
Rotor Power Required (must define for each rotor)	tiploss	tip loss factor B (lift zero from BR to tip)
	Ki_hover	hover induced velocity factor (ratio to momentum theory induced velocity)
	Ki_climb	axial climb induced velocity factor
	Ki_prop	axial cruise induced velocity factor (propeller)
	Ki_edge	edgewise flight induced velocity factor (helicopter)
	Ki_min	minimum induced velocity factor
	Ki_max	maximum induced velocity factor
	CTs_hind	induced blade loading for induced velocity variation with thrust in hover
	kh2	coefficient for induced velocity variation with thrust in hover
	mu_edge	advance ratio for induced velocity variation with edgewise velocity for Ki_edge
	CTs_Pind	induced blade loading for induced velocity variation with thrust in axial cruise
	ke1	linear coefficient for induced velocity variation with edgewise velocity
	ke3	exponent coefficient for induced velocity variation with edgewise velocity
	Xe	exponent for induced velocity variation with edgewise velocity
	CTs_Dmin	blade loading for minimum profile drag
	d0_hel	constant for drag equation in hover/edgewise
	d0_prop	constant for drag equation in prop (axial)
	d2_hel	quadratic term for drag equation in hover/edgewise

	d2_prop	quadratic term for drag equation in prop (axial)
	CTs_sep	blade loading for separation (changes cdbasic)
	dsep	factor for drag increment (multiply by difference in blade loading wrt to separation blade loading)
	Xsep	exponent for difference in blade loading wrt to separation blade loading
	fstall	constant in stall drag increment
	dstall1	factor in stall drag increment
	dstall2	factor in stall drag increment
	Xstall1	exponent in stall drag increment
	Xstall2	exponent in stall drag increment
	Mdd0	drag divergence mach number at zero-lift
	dm1	linear coefficient in drag increment
	dm2	exponent coefficient in drag increment
	Xm	exponent in drag increment
Fuel Flow	sfc0C_tech	specific fuel consumption at MCP technology factor
	SPOC_tech	specific power at MCP technology factor
	Kffq0	constant for referred fuel flow required at power required
	Kffq1	constant for referred fuel flow required at power required
Power Available	fPloss_inlet	engine inlet loss
	fPloss_exh	engine exhaust loss
	fPloss_xmsn	gear box loss (fraction total component power required)
	eta_d	engine inlet efficiency
	Nspec_tech	
	Kspa0	piecewise linear $K_{spa} = K_{spa0} + K_{spa1} \cdot \theta$, K_{spa} is static lapse rate
	Kspa0	
	Kspa0	
	Kspa0	piecewise linear $K_{spa} = K_{spa0} + K_{spa1} \cdot \theta$, K_{spa} is static lapse rate
	Kspa0	
	Kspa0	
	Kspa0	piecewise linear $K_{spa} = K_{spa0} + K_{spa1} \cdot \theta$, K_{spa} is static lapse rate
	Kspa0	
	Kspa0	
	Kspa1	piecewise linear $K_{spa} = K_{spa0} + K_{spa1} \cdot \theta$, K_{spa} is static lapse rate
	Kspa1	
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	Kspa1	piecewise linear $K_{spa} = K_{spa0} + K_{spa1} \cdot \theta$, K_{spa} is static lapse rate
	Kspa1	
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	Kspa1	piecewise linear $K_{spa} = K_{spa0} + K_{spa1} \cdot \theta$, K_{spa} is static lapse rate
	Kspa1	
	Kspa1	
	Kspa0	piecewise linear $X_{spa} = X_{spa0} + X_{spa1} \cdot \theta$, X_{spa} is inlet ram air exponents
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	Kspa0	piecewise linear $X_{spa} = X_{spa0} + X_{spa1} \cdot \theta$, X_{spa} is inlet ram air exponents
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	Kspa1	piecewise linear $X_{spa} = X_{spa0} + X_{spa1} \cdot \theta$, X_{spa} is inlet ram air exponents
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	Kspa1	piecewise linear $X_{spa} = X_{spa0} + X_{spa1} \cdot \theta$, X_{spa} is inlet ram air exponents
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	Kspa1	piecewise linear $X_{spa} = X_{spa0} + X_{spa1} \cdot \theta$, X_{spa} is inlet ram air exponents
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	Kspa1	

4.2 Survey of Technology Forecasting Techniques for Complex Systems

Survey of Technology Forecasting Techniques for Complex Systems

Executive Summary

This research seeks to review and characterize technology forecasting techniques to create a taxonomy for use in complex system analysis. Previous research with the Capability Assessment and Tradeoff Environment (CATE) identified a need for improved technology analysis methods. Past technology assessments for CATE relied on the expert elicitation for technology assessment, which resulted in poor forecasts due to various factors associated with the technique. Understanding technology forecasting options and their correct application will remedy the problems encountered by the CATE research team and other groups involved in forecasting studies.

The research is accomplished in three steps. First, techniques referenced by existing literature surveys on the subject are extracted and compiled together. Second, a text mining approach is demonstrated for screening literature and identifying any recently developed techniques. Third, the techniques' associated literature is reviewed to characterize each technique based on criteria relevant to complex systems. A few suggestions are given for technique selection based on the taxonomy to illustrate its value.

There are three major outcomes of this research – application of text mining for extracting new developments in technology forecasting, an exhaustive taxonomy of techniques indicating their characteristics and outcomes, and a suggested approach for selecting a combination of techniques for complex system technology forecasting. Fifty-eight techniques are extracted from literature survey. An analysis of 12,000 research database results found two new methods – a class of methods using artificial intelligence, and a unique technique called Fuzzy Cognitive Maps. The taxonomy is created for the sixty methods by classifying them based on family, quantitative or qualitative, explorative or normative, expected results, and then characterized according to twelve criteria taken from literature. The criteria covers aspects of the techniques ability to make predictions relevant to its development time frame, life cycle, evolution, social and economic impacts, and improvements. The criteria also considers the ease and cost of applying the technique. A technique can be selected from the taxonomy by first considering the desired result(s) to create a subset(s) of techniques, then weighting their technology on criteria related to the given technique criteria, and then applying a multi-criteria decision-making method to make the final selection(s).

The analysis to find new techniques is similar to the bibliometric forecasting method and results in a few lessons learned. Simply performing factor map and principal component decomposition on the cleaned natural language processing results is not likely to return any significant phrases. Of the nodes returned in this analysis, most are placed into an “other” node. A keywords and key phrases list to represent the “language” of the field is necessary to extract useful information from the databases. Second, the results of text mining will need to be scrutinized to ensure they are relevant to the information desired. These lessons indicate that the process is more hands-on than some texts indicate.

The taxonomy can be improved by eliciting ratings from technology forecasting experts. The limited time frame of this research made interaction with experts infeasible as contacting them, creating questionnaires, receiving feedback, evaluating feedback, and iterating until consensus is a lengthy process. Future work in this field should refine and formalize the selection methodology by applying it to several different complex system technologies. Given the existing selection methods, which give single techniques, the method should instead focus on forecasting a complete ecosystem for each technology in a simplified manner. Additionally, researchers will benefit by working with technology forecasting experts to refine the dimensions for complex systems and match these dimensions with the expected results and family categorization of the forecasting techniques. These improvements will increase the efficiency and repeatability of technology forecasting studies for complex systems.

This study demonstrates the use of text mining for consuming a large body of literature for new technology forecasting techniques. However, this approach can be applied to any field where researchers want to identify the frontiers of its research. Finally, the forecasting technique taxonomy created through this research provides a valuable resource for awareness and application of technology forecasting techniques.

Survey of Technology Forecasting Techniques for Complex Systems

Andrew Smith

AE 8900 MAV – Special Problems, Spring 2016

Complex system design and assessment is a challenging task exasperated by the need to forecast nascent technology in system evaluation. Proper technology forecasting technique selection will assist decision-makers to understand the risks involved in the integration of emerging technology into existing or new complex system developments. This research surveys the field of technology forecasting using both previous technology forecasting survey results and text mining on academic literature to identify 60 unique technology forecasting methodologies and associated variations. Then, the literature for the technologies is reviewed to place the technique into a family, describe whether it was quantitative or qualitative, indicate whether it could be used for explorative or normative forecasting, rate 12 criteria, and characterize the expected results of the technique. A technology forecasting taxonomy is created from these results. This taxonomy can be used to guide the designer or decision maker to select the most appropriate technique based on the purpose of a forecasting exercise, the characteristics of the technology to be forecasted, and the amount of effort and resources that can be expended for the exercise.

I. Introduction

IN engineering, technology forecasting is concerned with the desire to forecast the impact a technology might have on system performance.¹ The design of complex systems generally relies on performance estimates for decision-making. Complex systems are characterized by their large number of components and their interactions with each other and the environment. Assessing complex system performance can be difficult since interactions may be dynamic or not well understood and because the whole is more than the sum of the parts.² Assessing nascent technology integration into complex system designs introduces uncertainties about the technology's impact for decision-makers to manage in addition to uncertainties in system performance due to complexity. Proper selection and application of technology forecasting techniques will give decision-makers an improved understanding of the uncertainties they must manage, as well as multiple aspects to consider in their decision-making process. This study seeks to review and characterize applicable technology forecasting techniques for use in complex system analysis and create a technology forecasting taxonomy for reference in future studies. First, the problem motivation is discussed, followed by relevant background information on technology forecasting. Then, a literature review on the state of technology forecasting in Aerospace Engineering and any relevant technology forecasting surveys is given. Next, the approach and results for finding, reviewing, and characterizing technology forecasting is discussed. This study utilizes text mining to identify technology forecasting techniques not previously mentioned in technology forecasting surveys. Finally, the paper is concluded by discussing technique selection using the taxonomy as well as suggestions for forecasting on multiple dimensions.

II. Motivation

Previous research with the Capability Assessment and Tradeoff Environment (CATE) identified a need for improved technology analysis methods.³ CATE uses “k-factor” technology representation to estimate performance impacts, which allows for quantitative representations by estimating impacts as changes with respect to variables’ baseline values.^{4,5} Past technology assessments for CATE relied on the Delphi method, or expert elicitation, to estimate technology k-factors. In using the Delphi method, researchers faced three difficulties. First, researchers had to educate Subject Matter Experts (SMEs) on this representation method, which is a departure from how they viewed technologies. In researchers’ experiences, SMEs are more concerned with how to get a technology functioning rather than how it might improve or change a system. Second, locating and contacting an appropriate number of SMEs was challenging given how few they might be for a given field. Finally, SMEs were prone to give biased estimates because

they need to “sell” their technology. These factors lead to poor technology forecasts, which diminish their value for decision-makers.³

Understanding technology forecasting options and correct application of the techniques will remedy the problems encountered by the CATE research team and other groups involved in forecasting work. As a first step in creating valuable forecasts, the identification of relevant forecasting techniques for complex systems will enable future technology researchers to easily select and apply techniques to their specific studies.

III. Background

Technology forecasting can be broadly characterized as exploratory or normative. Exploratory forecasting techniques use historical trends to extrapolate into the future to predict what might happen. Normative forecasting techniques start with future goals and attempt to identify necessary levels of technological improvement.⁶ There are four general techniques that exploratory and normative forecasting methodologies use: judgmental or intuitive methods, extrapolation and trend analysis, models, and scenarios and simulations. Judgmental methods use opinion-based forecasts. These can be disproportionately biased by dominant participants. An example of a judgmental method is the previously mentioned Delphi method. The Delphi method is a structured methodology using questionnaires and feedback to elicit expert opinion to estimate technology impacts. This is the preferred method when insufficient information exists. Extrapolation and trend analysis use historical data for making forecasts. S-curves, or growth curves, are an example of this methodology type. S-curves assume a functional form of a previous or existing technology growth pattern. The drawback of this method is the large amount of information necessary. Models assume that information is available to construct and solve the model that leads to a forecast at some time in the future. Finally, scenarios and simulations assume a future status of the world and its influence on a technology to shape the development curve.⁷

A committee assembled to create a persistent disruptive technology forecast methodology suggest using many techniques to generate forecasts in order to avoid creating poor forecasts, even with credible data.⁷ Joseph Martino and John Vanston both give discussions on ranges of techniques to use. Martino suggested a broad set of dimensions to consider: technological, economic, managerial, political, social, cultural, intellectual, religious, and ecological.⁸ Vanston suggests a concise set of five views: the future as a logical extension of the past, an intuitive view based on experts, pattern analysis, goal analysis, and counter puncher.⁹ Other researchers have also suggested taking a multi-faceted approach to ensure that the ecosystem surrounding emerging technologies is fully considered.¹⁰

IV. Literature Review

There are two main areas to review literature. The first is in Aerospace Engineering, where a significant amount of work is done in designing complex systems. The second area is to look for previous surveys of technology forecasting techniques.

A. Technology Forecasting Techniques in Aerospace Engineering

In Aerospace Engineering, there are two main areas related to technology forecasting. Researchers either conducted a technology-specific assessment^{11,12,13} or estimated the impacts of many different technologies for various complex system applications.^{14,15,16,17 18} The first approach gives sub-system and component level predictions. The second approach propagates forecasts at lower-levels to system-level, or overall, impacts. This approach is generally for managing technology portfolios. CATE is one of these tools.

The general methodology for creating the technology impact environments is based on Technology Impact Forecasting (TIF)^{4,19,20} and Technology Identification, Evaluation, and Selection (TIES).²¹ TIF aims to assess the required capabilities to meet system performance objectives.^{4,19,20} TIES is an approach to assess specific technologies' impact on system performance. Additionally, TIES links technology readiness levels with uncertainty in impact estimates and then uses probabilistic tools to assess uncertainty in future technologies.²¹

A few other studies have looked at implementing new techniques to assess technology k-factors. A recent study briefly discusses expanding technology assessment methods, specifically data mining and mathematical models built on category theory, graph theory, and formal concept analysis.²² In an older study, multi-dimensional growth models for technology attributes are developed, which aids in complex system evaluation. This methodology relies on estimating the upper physical limits for all attributes and thus provides a framework for evaluating the technological limits of a system for a given set of technologies.²³ Another study combined Technology Synergy Methodology, which captures 2nd and higher order interaction effects between technologies, with Dempster-Shafer theory in order to quantify epistemic uncertainty. This methodology allows for multiple, potentially conflicting, SME beliefs to be aggregated and provide a better understanding of the uncertainty.²⁴ In this author's experience, both of these studies

have not been widely adopted in the TIF and TIES environment creation projects likely due to the complexity of their processes. Instead, these TIF/TIES environments tend to rely on the Delphi method or the technology assessments from other sources. The current TIF/TIES environments also lack the multi-faceted technology forecast approach suggested by Martino and Vanston.

B. Previous Surveys of Technology Forecasting Techniques

Several survey studies of the technology forecasting field have been conducted. Most recently in 2013, Cho and Daim provided a fairly comprehensive survey of technology forecasting methods and their origins up to the date of the research.²⁵ Additionally in 2013, Kang, Jang, Lee, and No investigated developments and patterns of technology research over time as well as matching industries and methods.²⁶ In 2010, The National Research Council Committee on Forecasting Future Disruptive Technologies reviewed the high level forecasting techniques and highlighted a few recent advances.⁷ In 2008, Firat, Woon, and Madnick summarized technology forecasting techniques and applications. They specifically answered questions about strengths and weaknesses of techniques. The researchers reviewed popular techniques in 9 major families: expert opinion, trend analysis, monitoring and intelligence, modeling and simulation, scenarios, statistical, descriptive, creativity, and valuing / decision / economics methods. As a result, the report provides discussions on overlapping forms of forecasting technology developments and impacts.²⁷ In 2004, the Technology Futures Analysis Methods Working Group surveyed several different fields where technology forecasting, or assessment, was occurring. They synthesized the various methods employed into a table, which indicates the method's family, the qualitative or quantitative nature of the data used in the method, and if the technique is explorative or normative.²⁸ In 2003, Martino summarized recent advanced in both methodology improvement and novel methodologies.²⁹ In 2001, Slocum and Lundberg reviewed families of forecasting methods with a focus on TRIZ methods.³⁰ In 1998, Meade and Islam reviewed technology forecasting selection and model combinations, resulting in some guidelines for using multiple models. However, their research focused on diffusion models.³¹ Finally, in 1991, Porter, Roper, Mason, Rossini, and Banks reviewed methods by the parameters being forecasted.³²

There have also been several studies to investigate methodologies for technique selection. In 2013, Intepe, Bozdag, and Koc created a method using fuzzy technique for order preference by similarity to ideal solution (TOPSIS) to find the most appropriate technique as evaluated on 7 selection criteria.³³ In 2008, Cheng, Chen, and Chen performed a similar study with 8 criteria and a fuzzy analytic hierarchy process (AHP) for method selection.³⁴ In 2002, Mishra, Deshmukh, and Vrat provided a methodology for matching forecasting technique and technology on 22 characteristics.³⁵

As to this author's knowledge, there are no studies which indicate systematic ways to combine techniques to create the complete forecasting ecosystem. The studies which create methodologies for selecting a forecasting technique did not apply the process to all available techniques, nor did surveys attempt to characterize expected results from the technique. This study intends to re-survey the technology forecasting field to find any recent developments, and then characterize each technique based on criteria relevant to complex systems to create a technology forecasting taxonomy, which includes the type of expected results. Finally, using the expected results, the research will suggest combinations of techniques which result in a well-rounded forecast.

V. Approach

A review of technology forecasting techniques is conducted in three steps with the end goal of creating a technology forecasting taxonomy for complex systems.

1. Technology forecasting techniques and methods are extracted from the previously discussed technology forecasting surveys.
2. Databases are queried for technology forecasting methods and the results combined and analyzed for new techniques.
3. Relevant papers for the identified techniques are identified and reviewed to characterize each technique based on the criteria relevant for complex systems. Additionally, expected results of the forecasting technique are categorized.
4. The characterization and result categorization are assembled into a technology forecasting taxonomy to help future researchers efficiently select techniques.

Finally, some suggestions are given for technique selection based on the taxonomy and literature for considering multiple dimensions.

In step 2, records are taken from the ProQuest Research Library, EBSCO Academic Search Complete, and Web of Science. These databases are selected due to their breadth of topics. They are also basic research databases, which are assumed to contain any recent advances in technology forecasting. The search terms used are *technology NEAR/2*

*forecast**, *technology NEAR/2 trend*, *technology NEAR/2 trajectory*, *technology NEAR/2 foresight*, *tech* NEAR/2 intelligence*, *forecast* NEAR/2 technique*, and *forecast* NEAR/2 methodology*. The phrase *NEAR/2* activates proximity searches where results with the terms before and after *NEAR/2* are within 2 words of each other. The search item *tech* NEAR/2 intelligence* is used to find results from industry methods that use the terminology “technology intelligence” and “competitive technical intelligence”, so these terms are included to capture any relevant articles.²⁷ Any articles related to meteorology or demand forecasting are removed. VantagePoint text-mining software is used to remove duplicate records and to rapidly consume abstract information. VantagePoint provides tools to clean text with a thesaurus and then use Natural Language Processing (NLP) to extract words and phrases.³⁶ The most challenging aspect of this work is analyzing the large body of literature on the subject of technology forecasting. VantagePoint utilizes text mining to greatly enhance assessing literature. To find new forecasting methods, a key word list is generated from the extracted techniques from the surveys. Then, VantagePoint is used to pull these key words from the abstracts. Next, VantagePoint’s NLP algorithm is used to extract general phrases from the abstracts. A co-occurrence matrix is used with the key word list and the NLP phrases to find where the key words do not occur with the NLP phrases as they may be new techniques. These “new technique phrases” are hand-reviewed to remove any phrases that are known to not be related to a technique. Then, the “new technique phrases” are analyzed using both a factor map and principal component decomposition (PCD). The factor map analysis uses small-increment Kaiser Varimax Rotation to cluster phrases together that capture the most records, while the PCD analysis creates co-occurrence-based principal components to cluster phrases together to capture the most records.³⁷ Both analyses will filter the results into areas of technology forecasting research, which are then be explored to identify if it is a new technique or not.

In step 3, the general techniques identified in step 2 are reviewed to classify and identify characteristics relevant to complex systems. These characteristics are a subset of the characteristics mentioned in the literature^{33,34,35} and are given in Table 1.

Table 1. Technology Forecasting Technique Criteria

Criteria	Reference
Capability to forecast incremental change	35
Capability to forecast radical innovations	35
Capability to forecast modular technologies	35
Life cycle prediction capability	35
Capability to forecast for stipulated time horizon	35
Data availability	33, 34, 35
Data validity	33, 34, 35
Technology development predictability	33, 34, 35
Technology similarity	33, 34, 35
Method of adaptability	33, 34, 35
Ease of technique implementation	33, 34, 35
Cost of technique implementation	33, 34, 35

Technology forecasting for complex systems is largely concerned with how the particular system’s behavior will change and not necessarily replacements for the complex system. For forecasting, techniques concerned with diffusion or acceptance of technology are not relevant. The criteria selected for evaluating techniques ensures that the character of the technology change is considered (incremental change, radical change, or modular behavior), the life cycle of the technology, the time frame for which a technology is being considered, what is known about the technology currently (data availability and validity), and the similarity of the technology to previous technologies. Additionally, the criteria considers how the technique is implemented, as users are not likely to attempt difficult or expensive methods (ease and cost of technique implementation). After the techniques are characterized, the expected results are also characterized to give researchers an indication of what to use the technique for. The characterizations from step 3 are considered in conjunction with literature consensus on multiple dimensional forecasting. This work will provide future researchers a quick technique reference for use in forecasting exercises with complex systems.

VI. Implementation and Analysis

There are three major outcomes of this research – a list of possible technology forecasting techniques, a taxonomy of techniques applicable to complex systems and their characteristics and outcomes, and a discussion on selecting a combination of techniques for complex system technology forecasting.

A. Technology Forecasting Techniques

Two hundred individual techniques are extracted from the technology forecasting surveys. The table given by the Technology Futures Analysis Methods Working Group is used as a starting point for assembling a matrix because it categorizes techniques by family (Creativity, Descriptive and Matrices, Expert Opinion, Modeling & Simulation, Scenarios, Statistical, Trend, and Valuing/Decision/Economic), quantitative or qualitative, type (Explorative or Normative), and gives references for further information about the technique.²⁸ There are 51 techniques given in the table. Comparing these techniques with the other surveys indicated that the methods listed by the Technology Futures Analysis Methods Working Group consist of many different variations (especially for trends, where Meade and Islam list 29 different curves³¹). The techniques from the other surveys are reviewed for addition to the table, resulting in adding the following 7 techniques: Artificial Neural Networks (ANN), causal layered analysis, collaborative methods, heuristic methods, hybrid models, tech sequence analysis, and wild cards.

All of the techniques extracted from the surveys are used to create a keyword list for analyzing research databases. Approximately 12,000 papers are returned from the research database queries. The search results are uploaded into VantagePoint and then cleaned to remove duplicates based on author and paper title. Then, the keywords are input into VantagePoint. VantagePoint searches the abstracts to find and pull the keywords from the papers. Then, VantagePoint's NLP algorithm is applied to the abstracts to pull phrases. These phrases are cleaned twice – first to change any British spellings to American (using the British thesaurus) and then cleaned using a general fuzzy algorithm, which truncates words to their root. Next, a co-occurrence matrix analysis is created to see where the

keywords and NLP phrases occurred together and where they did not. The matrix is filtered to remove results with more than 1 co-occurrence. Then, the remaining NLP phrases are selected and used to create a subgroup within the NLP phrase list. This group is reviewed by hand to remove phrases that are known to not be techniques (such as the publishing company name Elsevier). This sub-group is then analyzed using both the factor map and the PCD analyses available in VantagePoint. Figure 1 shows the Factor Map for potential new forecasting techniques. The lines between the nodes indicate that the terms are related by being included in the same record(s). The map indicates the following potential techniques:

- Bayesian methods
- Genetic programming
- Collaborative foresight
- Real-time forecasts
- Hybrid approach
- Artificial intelligence
- Fuzzy methods

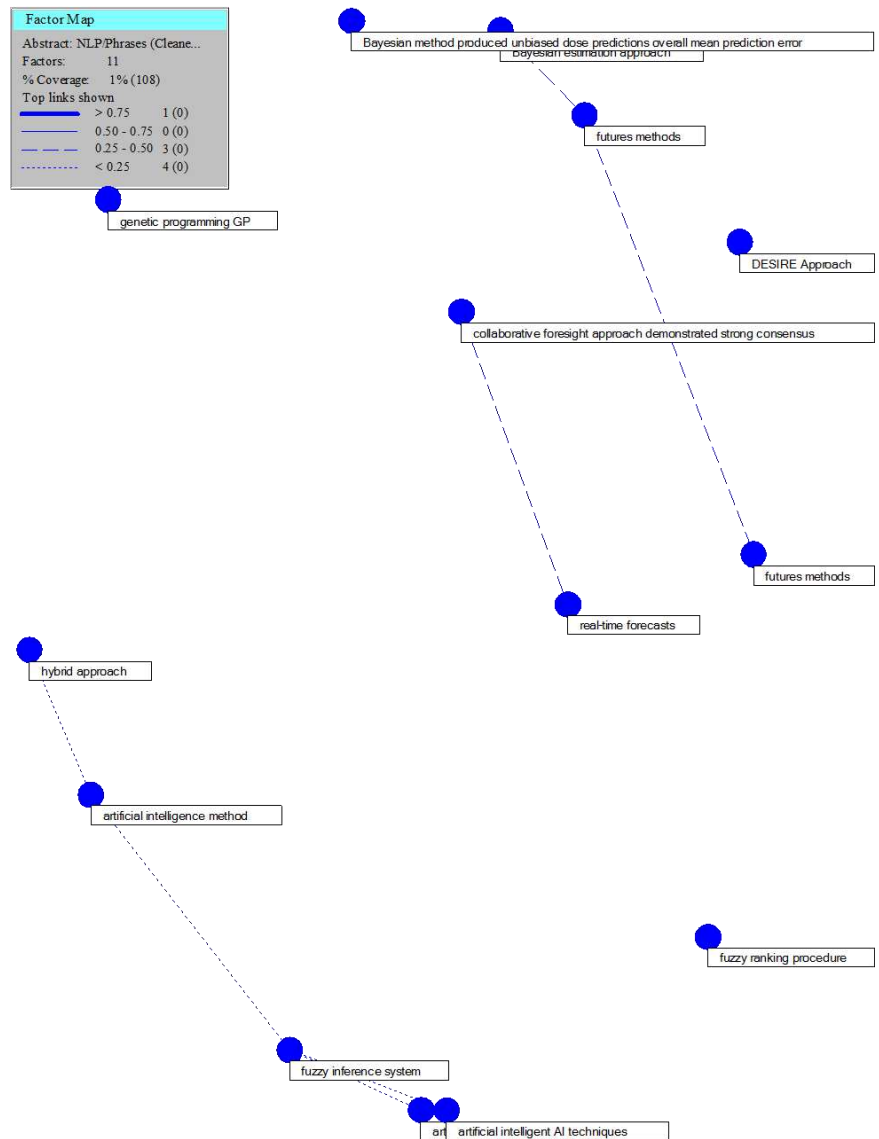


Figure 1. Factor Map of Potential New Forecasting Techniques

The other phrases (futures methods and DESIRE approach) are unrelated phrases to forecasting techniques. Of the potential techniques listed, Bayesian methods, collaborative foresight, and hybrid approach are already included in the surveys. These terms were not a part of the key word list, so the list of phrases of potentially new techniques included them. Additionally, genetic programming is considered part of heuristic methods by this author. The term genetic programming was also not included in the key words. When using this technique, failing to include all of the correct terms results in some older techniques remaining in the analysis. The remaining techniques to review for

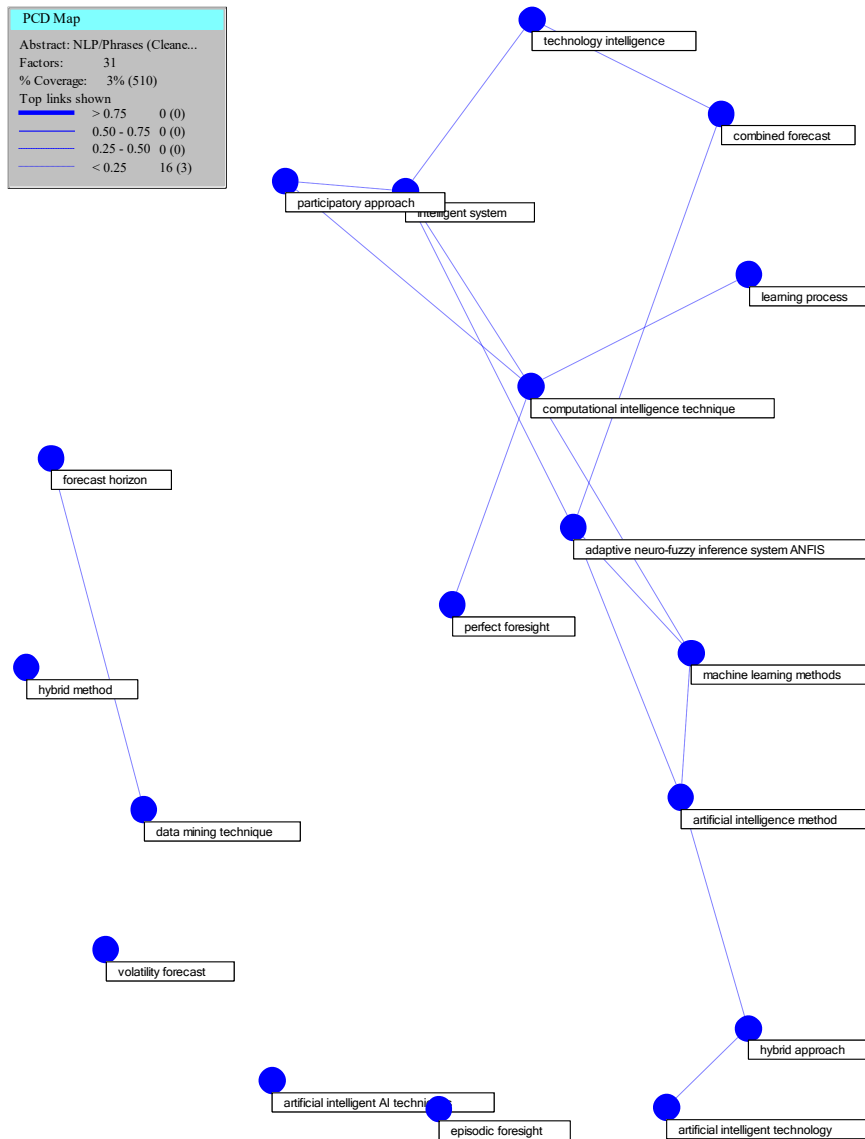


Figure 2. Principal Component Decomposition Map of Potential New Forecasting Techniques

possibility of inclusion in the updated technology forecasting taxonomy are Bayesian methods, real-time forecasts, artificial intelligence, and fuzzy methods.

Before reviewing these phrases, the Principal Component Decomposition analysis is used in an attempt to uncover other possible techniques and to compare methods. Figure 2 shows the map created using Principal Component Decomposition. The map indicates the following potential techniques:

- Combined forecast
- Learning process
- Participatory approach
- Computational intelligence
- Perfect foresight
- Fuzzy methods
- Machine learning
- Artificial intelligence
- Hybrid approach
- Data mining
- Volatility forecast
- Episodic foresight

The other phrases (technology intelligence and management system) are unrelated to forecasting techniques. The key word list included phrases similar to participatory, combined forecast, hybrid approach, and data mining (part of bibliometrics), but not explicitly these words. This

again reinforces how sensitive this technique is to its inputs. The remaining techniques are learning process, computational intelligence, perfect foresight, fuzzy methods, machine learning, artificial intelligence, volatility forecast, and episodic foresight. This analysis produced many more results than the factor map. However, the factor map analysis gave two results that the PCD did not (real-time forecasts and Bayesian methods). Of the PCD results, the factor map only gave artificial intelligence and fuzzy methods. The difference in results is due to different data reduction techniques used by factor map analysis and PCD.

The research papers associated with the phrases are reviewed to check that they are actual techniques for forecasting. Two new techniques emerged: artificial intelligence^{38,39} and the fuzzy cognitive map.⁴⁰ Machine learning

is generally considered subset of artificial intelligence in computing fields, so this technique is considered a variation of artificial intelligence methods.

Both factor map and PCD identified artificial intelligence and fuzzy method as new forecasting techniques. Factor map is more efficient as it represented the NLP phrase list of potential new techniques with 13 phrases compared to PCD's 18 phrases. However, PCD ran faster and could handle larger data sets than the factor map analysis.

The text mining method to find new techniques is similar to bibliometric forecasting, so the insights from this study are useful for future applications. First, performing factor map or PCD analysis on the cleaned NLP phrases may not return any significant results. Of the nodes returned in this study, most records are placed into an "other" node, which is useless information. A keywords and key phrases list representing the "language" of the field are necessary to extract useful information from the database records. For applying bibliometric techniques to complex systems, describing the system using functional words will be invaluable for creating the key word list. Second, the results of text mining will need to be scrutinized to ensure they are relevant to the information desired. The application of text mining illustrates its power, but the lessons learned indicate that the method may be less straightforward than some literature indicates.

B. The Complex System Technology Forecasting Taxonomy

After collecting the techniques, they are classified based on family, quantitative or qualitative, and explorative or normative. They are additionally characterized by the criteria in Table 1, which are defined as follows:

- *Capability to forecast incremental change* indicates how well the technique can handle evolutionary technology predictions, such as derivative designs.³⁵
- *Capability to forecast radical innovations* indicates how well the technique can handle revolutionary technology predictions, or blank sheet designs.³⁵
- *Capability to forecast modular technologies* indicates how well the technique can handle technologies whose components can be re-arranged and/or swapped to provide different functionality.³⁵
- *Life cycle prediction capability* indicates how well the technique is suited to all aspects of a technology's life, from inception to obsolescence of the technology.³⁵
- *Capability to forecast for stipulated time horizon* indicates how well the technique is suited for long-term forecasting. Ratings of 0 indicate short-term and ratings of 1 indicate long-term.³⁵
- *Data availability* is the quantity of data required to use the technique.³³
- *Data validity* is how well the data should correspond to the metric of interest for the technique.³³
- *Technology development predictability* indicates how suited the technique is to predicting the movement of technology from basic research to production.³³
- *Technology similarity* indicates how similar the new should be to an existing technology to use the technique.³³
- *Method of adaptability* indicates the extent to which the technique depends on expert opinions (higher rating indicates higher reliability on experts).³³
- *Ease of technique implementation* indicates how easy it is to grasp and apply the technique.³³
- *Cost of technique implementation* indicates expected level of resource commitment to apply the technique.³³

Additionally, the expected results are characterized using the following definitions based on literature associated with each technique.

- *Acceptability* indicates that the technique will or will not be acceptable to a society, while *rate* is used to clarify that the technique will give an indication of adoption.
- *Alternatives* means that several options for a function that a technology performs will be given or that several scenarios surrounding the technology will be given.
- *Any* indicates that the technique is flexible enough to be used to generate whatever the user desires.
- *Behavior* is used to indicate when a technique helps users understand linkages between actions and trends and technology.
- *Decision* indicates that the technique is likely to prescribe what decision to make based on value.
- *Economic trends* or *economic value* indicates that the technique is concerned with the profitability of the technology.
- *Impact identification* indicates that the technique returns knowledge about where impacts of a technology can be expected.
- *Metric estimates* or *metric values* indicates that the technique returns actual values for metrics for which the technology is being measured.

- *Metrics* simply indicates that the technique indicates what metrics should be used to assessing a technology.
- *Obsolescence scenarios* indicates that the technique gives situations in which something is no longer necessary.
- *Probabilities of outcomes* indicates that the technique gives users an idea of the uncertainty of a particular event or metric value coming to fruition.
- *Roadmap to scenario* is used to separate a technique from technology development when the technique deals specifically with pathways to an event occurrence.
- *Technology development* is related to both the pathway of a technology from basic research to production as well as the timeline of the technology's development.

An example of the technology taxonomy is given in Table 2 illustrating the characterizations for one of the new techniques, artificial intelligence.

Table 2. Sample Technology Taxonomy

Method [variations]	Artificial Intelligence [Machine Learning]
Family	Statistical
Quant (H) or Qual (S)	H/S
Exploratory or Normative	Ex
Capability to forecast incremental change [0 - cannot, 1 - can]	1
Capability to forecast radical innovations [0 - cannot, 1 - can]	0
Capability to forecast modular technologies [0 - cannot, 1 - can]	0
Life cycle prediction capability [0 - cannot, 1 - can]	0
Capability to forecast for stipulated time horizon [0 - short-term only, 1 - any time frame]	0
Data availability [0 - none or little, 1 - significant]	1
Data validity [0 - weak, 1 -strong]	1
Technology development predictability [0 - cannot, 1 - can]	0
Technology similarity [0 - unsimilar, 1 - similar]	1
Method of adaptability [0 - no reliance on ExOp, 1 - full reliance on ExOp]	0
Ease of technique implementation [0 - easy, 1 - hard]	1
Cost of technique implementation [0 - cheap, 1 - expensive]	1
Expected Results for Complex Systems	Metric value
References	38, 39

The fully technology forecasting technique taxonomy is given in Table 4 in the Appendix. Table 4 lists 60 technology forecasting techniques and their variations, characteristics for each, and references for further information on the technique. This table is useful for users new to the field of technology forecasting to find techniques appropriate to their study. The characteristic values are based on reviews of literature. However, the taxonomy would be improved by eliciting ratings from technology forecasting experts. The limited time frame of this research made interaction with experts infeasible as contacting experts, creating questionnaires, receiving feedback, evaluating feedback, and iterating until consensus is a lengthy process.

C. Using the Taxonomy for Technique Selection

There are several ways to use the technology taxonomy to select a single technique. A simple method is described by Mishra and Deshmukh where a technology is rated on characteristics that align with the forecasting technique's characteristics. Next, a multi-criteria decision making technique is used to evaluate which technique the technology's score is closest to.³⁵ The technique described by Intepe, Bozdog, and Koc uses expert judgement combined with fuzzy logic to rate techniques on given criteria for a particular area.³⁴ Use Table 3 based on Ref. 33-35 for guidance on the technology characteristics that correspond with forecasting technique characteristics.

Table 3. Matching Technology Criteria for Technique Criteria

Technology Criteria	Technique Criteria
Evolutionary change	Capability to forecast incremental change
Revolutionary change	Capability to forecast radical innovations
Modularity of technology	Capability to forecast modular technologies
Life cycle	Life cycle prediction capability
Time frame of interest	Capability to forecast for stipulated time horizon
Existing data availability	Data availability
Existing data validity	Data validity
Technology readiness level	Technology development predictability
Existing similar technologies	Technology similarity
Amount of existing information	Method of adaptability
Time available for study	Ease of technique implementation
Resources available for study	Cost of technique implementation

With the above table, forecasters can rate the technology for each criteria, and then use multi-criteria decision making techniques such as *technique for order preference by similarity to ideal solution* (TOPSIS) to find techniques that match. Note that for *technology readiness level* and *amount of existing information* are inverse of the rating of the *technology development predictability* and *method of adaptability*. A high technology readiness level may not need a technique for development predictability. A large body of work regarding a technology may be able to use techniques that do not rely on expert opinions.

Neither of the previously discussed selection techniques consider forecasting for the entire ecosystem for a technology. Using the taxonomy in Table 4, users can use the “Family” and “Expected Results” category to match technique with a part of the ecosystem. For example, consider the 5 varieties given by Vanston: the future as a logical extension of the past, an intuitive view based on experts, pattern analysis, goal analysis, and counter puncher.⁹ Based on these criteria, users should select one technique from the Trend family (which gives metric values), a technique from the expert opinion (which can give any data that the user is requesting), a technique that gives insights on behaviors, a normative technique that gives information related to technology development or alternatives, and lastly, a creativity technique that gives alternatives. While these 5 forecasts give a variety of useful information about the technology in consideration, there are still other areas untouched, such as the life cycle of the technology, or social impacts. Adding these areas to the list of Vanston, or using the extensive list given by Martino,⁸ would cover more dimensions but also increase the workload of the technology assessment.

Not all complex system technology forecasts may benefit from a forecast in the same, broad areas. Instead of using all areas, technology forecasters and experts could evaluate the likelihood of a technology’s economic, managerial, political, social, cultural, intellectual, religious, and ecological impact (the dimensions given by Martino⁸). Note that these dimensions are in addition to the performance of the technology. To illustrate this idea, consider two nominal cases. Case A is evaluating a new rotor technology for an existing single main rotor system. Case B is the introduction of a new vertical take-off and landing (VTOL) short-haul vehicle for urban commuting.

In Case A, the new rotor technology, forecasters are likely to be most concerned with how it will impact system performance. In addition, they should be interested in its economic impact, managerial or development track, any political difficulties if it is for defense systems, and possibly ecological impacts such as noise. However, Martino’s other dimensions are not important for this particular technology. Following the performance impact, the technology’s economic and managerial forecasts will be most important. The analyst should select a technique that gives economic results with the high data availability and data validity *and* a technology development result technique with high data availability and data validity. Political and ecological issues may be secondary as it is a derivative technology, so the analyst should choose a technique from the expert opinion family for any political considerations (a defense firm may be interested in likelihood of upgrades being approved) *and* for evaluating how the rotor will affect the environment (such as noise). The analyst should then create 5 subgroups from the taxonomy for each of the previously mentioned taxonomies. Then, the analyst would use a technology-technique selection process described earlier within *each* subgroup, resulting in a multi-dimensional forecast to predict a relevant ecosystem for the technology.

In Case B, the VTOL short-haul vehicle, forecasters need to consider many more dimensions given the significant impact of such a vehicle on society. Almost all dimensions given by Martino should be considered with a high degree of importance. Unforeseen issues in the business case for this vehicle, difficulties with program management, difficulties in navigating safety requirements for transport aircraft, acceptance of the vehicle in society and integration into culture, and concerns over fuel emissions and noise issues could compromise the project.

Both cases are complex systems, but need different forecasting dimensions and techniques. However, forecasting in many dimensions will not remove the uncertainty surrounding a potential technology nor guarantee its success. The value of multi-dimensional forecasting is not in the improved accuracy of the prediction, but the additional knowledge that decision-makers have about the technology.

Future research should include examples using several different, real complex system technologies to refine selection methodology for forecasting an appropriate ecosystem surrounding the technologies. In this endeavor, researchers will benefit by working with experts to reach a consensus on relevant forecasting dimensions for complex systems. Researchers can then work to match these dimensions with the expected results and family characteristics of the forecasting techniques.

VII. Conclusion

This study surveyed the field of technology forecasting by looking at both previous literature surveys and text mining academic literature to identify 60 unique technology forecasting techniques and associated variations. The text mining demonstration illustrates the ability of the technique to find frontiers, which is applicable in any field of research. The demonstration also provided valuable lessons for researchers interested in using text mining. The literature associated with each technique was reviewed to place it into a family, describe whether it was quantitative or qualitative in nature, indicate whether it could be used for explorative or normative forecasting, rate 12 criteria, and characterize the expected results of the technique. This resulted in a comprehensive technology forecasting taxonomy. This taxonomy can use considerations about the purpose of a technology forecast, the characteristics of the technology, and the amount of expendable effort and resources to select an appropriate forecasting technique. Additionally, this taxonomy provides a valuable resource for awareness of technology forecasting techniques. For future work on the forecasting technique taxonomy, the criteria ratings and characteristics should be vetted by technology forecasting experts to remove any controversy in its use. Next, a framework for selecting forecasting dimensions followed by technique selection within each dimension should be built upon the technique taxonomy. These improvements will increase the simplicity and efficiency of technology forecasting studies for complex systems.

Appendix

Table 4. Complex System Technology Forecasting Taxonomy

Method [variations]	Family	Quant (H) or Qual (S)	Exploratory or Normative	Capability to forecast incremental change [0 - cannot, 1 - can]	Capability to forecast radical innovations [0 - cannot, 1 - can]	Capability to forecast modular technologies [0 - cannot, 1 - can]	Life cycle prediction capability [0 - cannot, 1 - can]	Capability to forecast for stipulated time horizon [0 - short-term only, 1 - any time frame]	Data availability [0 - none or little, 1 - significant]	Data validity [0 - weak, 1 -strong]	Technology development predictability [0 - cannot, 1 - can]	Technology similarity [0 - unsimilar, 1 - similar]	Method of adaptability [0 - no reliance on ExOp, 1 - full reliance on ExOp]	Ease of technique implementation [0 - easy, 1 - hard]	Cost of technique implementation [0 - cheap, 1 - expensive]	Expected Results for Complex Systems	References
Action [options] analysis	Valuing/decision/economic	S	Both	0	0	0	0	1	0.5	0	0	1	0.5	0	0	Economic value, Decision	
Agent modeling [Brownian agents]	Modeling and Simulation	H	Ex	1	1	1	0	1	1	1	1	0	0.5	0.5	1	Behavior	41 Ch. 31, 42, 43, 44, 45
Analogies	Descriptive and matrices	H/S	Ex	1	0	1	1	1	1	1	1	1	1	0	0	Technology Development	46
Analytic Hierarchy Process (AHP)	Valuing/decision/economic	H	N	0	0	0	0	1	0	0	0	0	1	0	0.5	Decision	47
Artificial Intelligence [Machine Learning]	Statistical	H/S	Ex	1	0	0	0	0	1	1	0	1	0	1	1	Metric value	38, 39
Artificial Neural Network [Adaptive neuro-fuzzy inference]	Modeling and Simulation	H	Ex	1	0	0	0	0	1	1	0	1	0	0.5	0.5	Metric estimates	7, 48, 49
Backcasting [Obsolescence forecasting]	Descriptive and matrices	S	N	1	1	1	1	1	0	0	1	0	1	0	0.5	Roadmap to reach scenario	7, 50
Bibliometrics [research profiling, patent analysis, text mining, citation network analysis]	Monitoring and Intelligence/Statistical	H/S	Ex	1	1	1	0	0	1	1	1	0	1	1	1	Technology development, Alternatives	41 Ch. 3, 51, 52, 53

Brainstorming [brainwriting, nominal group process (NGP)]	Creativity	S	Both	1	1	1	1	1	0	0	1	0	1	0	0.5	Alternatives, expert judgements	54
Causal Layered Analysis	Creativity	S	N	0	0	0	0	1	0	0	0	0	1	0	0	Behavior	50
Causal Models	Modeling and Simulation	H	Ex	1	1	1	0	1	1	1	1	0	0	0.5	0.5	Metric value	8
Checklists for Impact Identification	Descriptive and matrices	S	Ex	1	1	1	0	1	0	0	0	0	1	0	0.5	Impact Identification, Metric estimates	55
Collaborative [Prediction Markets, Online Forecasting Communities]	Expert Opinion	H/S	Ex	1	1	1	1	1	0	0	1	0	0.5	0	0.5	Any	7, 50
Complex Adaptive System modeling (CAS) [Chaos]	Modeling and Simulation	H	Ex	1	0	0	0	0.5	1	1	1	1	0	1	1	Technology Development	56, 57, 58
Correlation Analysis	Statistical	H	Ex	1	0	1	0	0.5	1	0.5	1	0.5	0	0.5	0	Metric value	8
Cost-benefit Analysis [Monetized and other]	Valuing/decision/economic	H	Ex	0	0	0	0	1	0.5	1	0	1	0.5	0	0	Economic value, Decision	59
Creativity workshops [future workshops]	Creativity	S	Both	1	1	1	1	1	0	0	1	0	1	0	0.5	Alternatives, expert judgements	60
Cross-impact Analysis	Modeling and Simulation / Statistical	H/S	Ex	1	1	1	0	1	0	0	1	0	0.5	0	0.5	Probabilities of outcomes	41 Ch. 9, 61
Decision analysis [utility analysis, influence diagrams, decision trees]	Valuing/decision/economic	S	Both	0	0	0	0	1	1	0	1	0	0.5	0	0	Probabilities of outcomes, Utility value	7, 62
Delphi [iterative survey]	Expert Opinion	S	Both	1	1	1	1	1	0	0	1	0	1	0	0.5	Any	41 Ch. 4, 63
Demographics	Statistical	H	Ex	0	0	0	0	1	1	1	0	1	0	0	0.5	Acceptability	
Diffusion modeling	Modeling and Simulation	H	Ex	1	1	1	0	1	0.5	0.5	1	0	0.5	0	0	Acceptability (rate)	64
Economic base modeling [input-output analysis]	Modeling and Simulation / Valuing/decision/economic	H	Ex	0	0	0	0	0.5	0.5	1	1	1	0	0.5	0	Economic trends, acceptability	65
Field anomaly relaxation method (FAR)	Scenarios	S	Both	1	1	1	0	1	0	0	1	0	0.5	0	0.5	Behavior	41 Ch. 30, 66
Focus groups [panels, workshops]	Expert Opinion	S	Both	1	1	1	1	1	0	0	1	0	1	0	0.5	Any	41 Ch. 23
Fuzzy Cognitive Map	Statistical / Expert Opinion / Scenarios	H/S	Ex	1	0	1	0	1	0.5	0	1	1	0.5	0.5	0.5	Behavior	40

Heuristic	Modeling and Simulation	H	Both	1	1	1	1	1	0.5	0.5	1	0	0.5	1	0	Metric value, behavior	50, 67
Hybrid models	-	H/S	Both	1	1	1	1	1	0.5	0.5	1	0	0.5	1	1	Any	68, 69, 70, 71
Innovation system modeling	Descriptive and matrices	S	Ex	0	0	0	0	0.5	1	1	1	0	0.5	0.5	0.5	Technology Development	72, 73, 74
Institutional analysis	Descriptive and matrices	S	Ex	1	0	1	0	1	0	0	1	0	0	0	0.5	Metric values	61
Interviews	Expert Opinion	S	Both	1	1	1	1	1	0	0	1	0	1	0	0.5	Any	
Long wave analysis	Trend	H	Ex	0	1	0	0	1	1	1	1	1	0	0	0.5	Technology Development	75, 76
Mitigation analysis	Descriptive and matrices	S	N	0	0	0	0	0.5	0	0	0	1	1	0	0.5	Obsolescence scenarios	
Monitoring [environmental scanning, technology watch]	Monitoring and Intelligence / Statistical	S	Ex	0	1	0.5	0	1	1	1	1	0	0	0.5	0.5	Technology Development	41 Ch. 2, 77
Morphological analysis	Descriptive and matrices	S	Both	0	1	1	0	1	0	0	0	0	1	0	0	Alternatives	78, 79
Multi-Criteria Decision Analysis [data envelopment analysis (DEA)]	-	H	N	1	0	0	0	0	0.5	0.5	0	1	0.5	0	0	Alternatives, Decision	80
Multiple perspectives assessment	Descriptive and matrices	S	Both	1	0	0	0	1	0.5	0.5	0	1	0.5	0	0.5	Behavior	41 Ch. 33, 81
Organizational analysis	Descriptive and matrices	S	Ex	0	0	0	0	0	0	0	1	1	1	0.5	0	Technology Development, Behavior	82
Participatory analysis	Expert Opinion	S	N	1	0	1	0	1	0	0	0	1	1	0	0.5	Any	41 Ch. 23, 83, 84
Precursor analysis	Trend	H	Ex	1	0	0	0	0	1	1	1	1	0	0.5	0	Technology development	8
Relevance Trees [futures wheel, future polygon]	Descriptive and matrices / Valuing/decision/ economic	S	Both	0	0	0	0	1	0	0	0	1	1	0	0	Behavior	41 Ch. 6-7 and 18, 85
Requirements analysis [needs analysis, attribute X technology matrix]	Descriptive and matrices / Valuing/decision/ economic	H/S	N	0	0	0	0	0	0.5	0.5	1	0	1	0	0	Technology Development, Metric values	
Risk analysis	Descriptive and matrices / Statistical	H/S	Both	1	1	1	0	1	0	0	1	0	1	0.5	0.5	Any, Probabilities of outcomes	86, 87
Roadmapping [product-technology roadmapping]	Descriptive and matrices	H/S	Both	1	0	0	1	0.5	1	0	1	1	1	0	0.5	Technology Development	88, 89, 90

Scenarios [Scenarios with consistency checks, Scenario management]	Scenarios	H/S	Both	0	1	1	0	1	0	0	0	0	1	0	0	Alternatives	41 Ch. 19 and 21, 91, 92, 93
Scenario-simulation [gaming, interactive scenario]	Scenarios / Modeling and Simulation	S	Both	0	1	1	0	1	0	0	0	0	1	0.5	0.5	Alternatives	41 Ch. 24, 94
Science fiction analysis	Creativity	S	N	0	1	1	0	1	0	0	0	0	1	0	0.5	Alternatives	
Social impact assessment [socioeconomic impact assessment]	Descriptive and matrices	S	Both	0	0	0	0	1	1	0	0	1	1	0	0.5	Acceptability	95
Stakeholder analysis [policy capture, assumptional analysis]	Descriptive and matrices / Valuing/decision/ economic	S	N	0	0	0	0	0	0	0	0	0	1	0	0	Metrics, Knowledge	96, 97
State of the future index (SOFI)	Descriptive and matrices	H/S	Both	0	0	0	0	1	1	0.5	0	0	0.5	0	0.5	Acceptability	41 Ch. 37
Sustainability analysis [life cycle analysis]	Descriptive and matrices / Modeling and Simulation	H	Ex	1	0	0	1	1	1	0.5	0	1	0.5	0.5	0.5	Alternatives, Metric values	98
Systems simulation [system dynamics, KSIM]	Modeling and Simulation	H	Ex	1	0	1	0	0.5	1	1	1	0	0	0.5	0.5	Metric values	41 Ch. 24, 99, 100, 101
Tech Sequence analysis [Project evaluation and review Technique]	Statistical / Expert Opinion	H/S	Ex	0	0	0	0	1	0.5	0	1	0	1	0.5	0.5	Technology Development	50
Technological substitution	Modeling and Simulation	H	Ex	1	1	1	0	1	1	1	1	0.5	0	0	0.5	Technology Development	102, 103, 104
Technology assessment	Descriptive and matrices / Modeling and Simulation	H/S	Ex	1	1	1	1	1	1	1	0	0	1	0.5	0.5	Metric values, Acceptability	61
Trend extrapolation [growth curve fitting and projection]	Trend	H	Ex	1	0	0	0	0	1	1	1	1	0	0	0.5	Metric values	8, 105, 106, 107
Trend impact analysis	Trend/Statistical	H	Both	1	0	1	0	0	1	1	1	1	1	0	0	Metric values	41 Ch. 8
TRIZ [patterns of evolution, Function]	Creativity	H	Both	0	0	0	0	1	0	0	0	0	1	0.5	0.5	Alternatives	30, 108, 109, 110
Vision generation	Creativity	S	Both	0	0	0	0	0.5	0	0	0	0	1	0	0.5	Alternatives	
Wild Cards	Creativity	S	N	0	1	0	0	1	0	0	0	0	1	0	0	Alternatives	7, 50

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